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Design Considerations for Upper Approaches to Navigation Locks

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Final report

ABSTRACT: Upper lock approach guard walls are structural features used by towboats to align with and enter the lock chamber. This report focuses on guard walls located in the upper lock approach. The performance of these guard walls drastically impacts the functional efficiency of any given lock. An efficient guard wall minimizes pilot maneuvering required to bring a tow to rest or near rest on the guard wall and align with and enter the lock chamber. In addition, guard walls are a major component in overall project cost.

Criteria for evaluating guard wall performance are general and limited. This report provides guidance so that engineers can design lock approach guard walls that are safe and efficient to the users, while being cost-effective. Both physical and numerical models were used to help research guard wall design and develop guidance for design. A literature review was used to assist in identifying pertinent design needs and to develop the testing and evaluation program. A physical model was constructed so that a detailed evaluation could be performed for selected guard wall designs. A numerical model was used to help rapidly evaluate numerous designs and identify the designs to refine in the physical model.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
miles (U.S. statute)	1.609344	kilometers
square feet	0.09290304	square meters
tons (force)	8,896.443	newtons
tons (2,000 pounds, mass)	907.1847	kilograms

Preface

The hydraulic analyses presented in this report were performed as a portion of the "Lock Approach Guidance" work unit (Work Unit 391003) of the Navigation Systems Research Program.

This work was conducted at the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC) during the period of December 1999 to September 2003 under the direction of Mr. Thomas W. Richardson, Director, CHL; Dr. William D. Martin, Deputy Director, CHL; and Mr. Donald C. Wilson, Chief of the Navigation Branch, CHL. Dr. Sandra K. Knight was the Technical Director for navigation studies and Mr. James E. Clausner was manager of the Navigation Systems Research Program.

The physical model investigation was lead by Messrs. Howard E. Park and Cecil Dorrell. Simulation runs and analyzes of results were conducted by Dr. Richard L. Stockstill. Drs. Stockstill and John E. Hite, Jr., and Messrs. Park and Timothy W. Shelton, who are all engineers in the Navigation Branch, wrote the report.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC. COL James R. Rowan, EN, was Commander and Executive Director.

1 Introduction

Background

Upper lock approach guard walls are structural features used by towboats to align with and enter the lock chamber. The guard wall is typically located on the riverside of the lock and serves (Figure 1) to guard against the tow being drawn towards the navigation dam during project discharges. A guide wall, on the other hand, is strictly an alignment mechanism that does not protect the tow from river flow. A guide wall is typically located on the landside of the lock as shown in Figure 1. This report focuses on guard walls located in the upper lock approach. The performance of these guard walls drastically impacts the functional efficiency of any given lock. Guard wall efficiency can be measured in units of time. An efficient guard wall requires the minimal amount of pilot maneuvering for a downbound tow to come to rest or near rest on the guard wall and align with and enter the lock chamber. In addition, guard walls are a major component in overall project cost. The cost of the guard and guide walls for proposed lock extension projects are estimated to be one-third of the overall project cost.
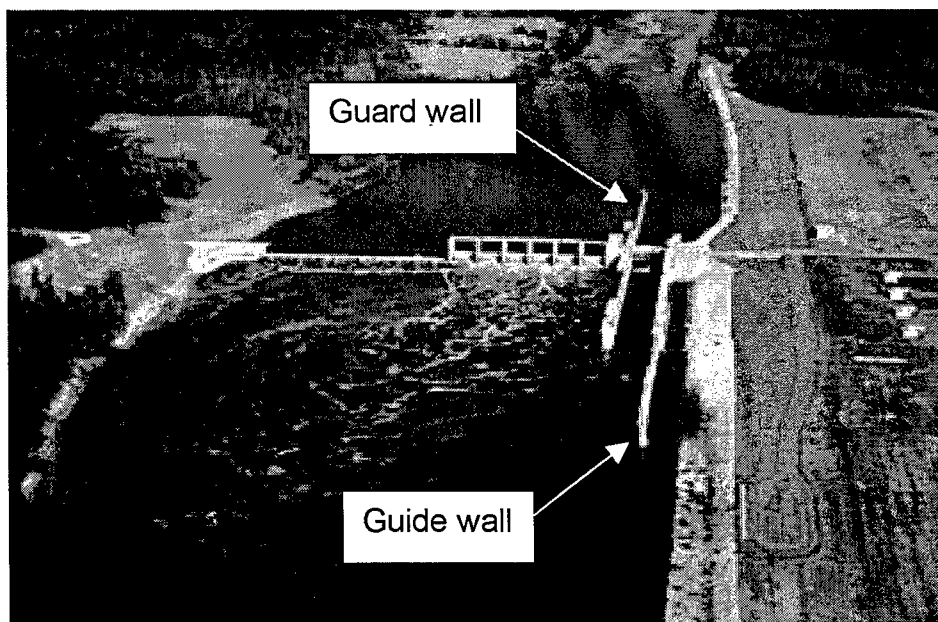
Figure 1.   Claiborne lock and dam, Alabama River, looking upstream

Criteria for evaluating guard wall performance are general and limited. Flow distribution along the guard wall and the ratio of total port area (port area is open area underneath the guard wall that allows flow towards the dam) to the intercepted flow area have been identified as factors that influence performance. The flow distribution along the guard wall refers to the incremental amount of the total flow under the wall that passes through each of the ported sections of the guard wall. The total area of these ported sections is designated A_p. Ported walls will be discussed in further detail in subsequent sections of the report. The intercepted flow area for an upstream guard wall refers to cross-sectional area of the approach channel between the upstream end of the guard wall and the bank. The intercepted flow area is designated A_x. Discharge entering the upper lock approach, or even the guard wall type may also be factors that affect guard wall performance. There have been several rules of thumb used in the past and numerous site-specific model studies that have been conducted to design guard walls that perform well. However, current hydraulic design guidance lacks detailed information to provide field engineers with the proper tools for determining appropriate guard wall geometry.

Guard walls are a necessary and integral part of the lock and dam project. It is nearly impossible to steer a vessel that is 32 m (105 ft) wide and 343 m (1,125 ft) long that weighs 27,000 tons metric (33,170 tons) into a lock opening that is 33.5 m (110 ft) wide without some means of aligning the vessel with the opening to the lock chamber as shown in Figure 2. Tows need some mechanism to come to rest or near rest on, align with, and enter the lock chamber. The mechanism is the guard wall.
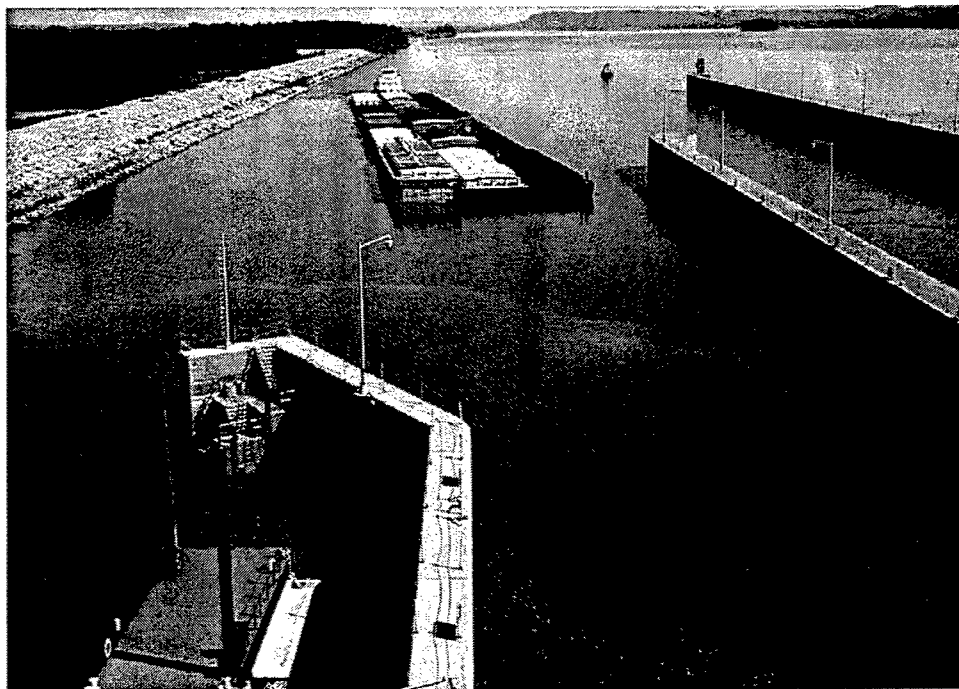
Figure 2. Downbound tow approaching lock

Guard Wall Geometry

Guard and guide walls are usually in both the upper and lower lock approaches. There are three basic types of guard walls currently used in upper lock approaches. These are multicell (ported and/or skirted or nonported), long span, and floating guard walls. A nonported guard wall is solid. Multicell guard walls consist of a series of circular driven cells spaced about 15 m (50 ft) on center with a concrete cap or precast beam connecting them together. The openings between the cells and below the concrete cap are the ports, and the distance between the cells is the span. The ported area for a multicell wall connected with precast beams is the sum of the areas between the cells from the bottom of the beam to the channel bottom. Often, this ported area is changed by the addition of skirts that hang from the beams between the cells. Various construction techniques can be used to build these walls. Sheet-pile cell walls filled with concrete or concrete capped, prefabricated steel cells filled with concrete which support spans of precast beams have been considered recently for guard wall designs.

Long span guard walls are basically the same as a multicell guard walls with span widths typically around 30.5 to 38 m (100 to 125 ft). The cap connecting the cells is normally a precast concrete beam that serves as the rubbing surface. Draft curtains or skirts can also be attached to the beam to regulate flow through the guard wall. Floating guard walls are generally a large hollow concrete pontoon. Floating walls are generally about 9 to 12 m (30 to 40 ft) wide and draft about 3 m (10 ft). Draft curtains attached to the bottom of the pontoon may also regulate flow under these walls.

Hydraulic Conditions Near Guard Walls

A guard wall is the aligning mechanism that also protects the tow from flow drawn toward the dam in the upper lock approach or from flow discharged from the dam across the lower approach. A tow moving in the direction of flow in the river must apply enough power to maintain steerage. In some instances a tow can be traveling between 5 and 10 knots downriver depending on river conditions and tow horsepower. However, as the tow approaches the lock, it must reduce power and forward speed to align with and enter the lock chamber at a speed of less than 1 knot. As the tow reduces forward speed to avoid a substantial impact to the guard wall or other structural features at the lock and dam project, it is susceptible to the currents in the immediate vicinity.

Outdraft

Typically, in the upper lock approach, the currents move across the lock approach towards the dam. The dam generally consists of a gated spillway section that controls the project discharges. The releases from the gated spillway direct the current in the upper approach to the spillway. These crosscurrents tend to direct the head of the tow toward the spillway. This condition is often referred

to as outdraft. Significant crosscurrents in the upper lock approach upstream of the guard wall can cause unsafe navigation conditions.

Draw

Ported guard walls with or without skirts and floating guard walls allow flow that enters the upper approach to pass underneath the wall towards the spillway. This condition is referred to as draw. If the flow under the wall toward the dam is excessive, the tow can be pinned against the guard wall. No crosscurrent in the upper lock approach upstream of the guard wall usually implies that all or most of the flow in the upper lock approach is passed through the guard wall and generally results in excessive draw toward the guard wall.

Determination of the optimum navigation conditions for a particular guard wall, requires balancing the forces produced by outdraft and draw towards the wall. A force balance is achieved by limiting outdraft by providing more flow area under the wall and using draft curtains to limit the draw toward the wall.

Navigation Conditions in Lock Approaches

Navigation studies often refer to navigation conditions. In general, this refers to the interaction between the vessel and the flow field that results in the degree of difficulty encountered maneuvering the vessel. Adjectives such as good, poor, safe, unsafe, and hazardous are frequently used to describe navigation conditions. All these adjectives relate to how difficult the tow is to maneuver. There are many factors that affect tow maneuverability in addition to the interaction between the vessel and flow field. Pilot experience, the horsepower of the vessel, and climatic conditions also affect tow maneuverability. Hazardous navigation conditions are described as those where there is a high probability that an accident can occur. Accidents in vicinity of navigation projects or features in the channel usually involve an uncontrolled impact with a structure. Poor navigation conditions in the lock approaches produce traffic delays and safety concerns. These conditions in upper lock approaches could be a result of too much outdraft or draw toward the guard wall. The performance of a particular guard wall with respect to its navigability is based primarily on these two factors and a properly designed wall results from a balance of these two conditions.

Hydraulic design guidance for guard walls is incomplete. Previously, rule-of-thumb and guidance from EM 1110-2-1611 (HQUSACE 1980) have been used to make a first cut design for upper and lower approach guard and guide walls.

Previous Investigations

Lock walls

Numerous site-specific studies have been conducted in support of development of navigation on the nation's waterways. One of the earliest was a model study for the Jim Woodruff Dam (U.S. Army Corps of Engineers 1952). This study found that approaches involving the use of slotted walls were superior in performance to solid walls. The solid walls reduced velocities in the upper lock approach, but intensified lateral flow passing around the upstream end of the lock wall. This forced the tow against the wall with considerable impact and the tow was then subject to being shunted around the lock entrance and crashing into the crest piers of the gated spillway. Model barge tow results clearly indicated the superiority of the slotted walls in the lock approach as compared to the solid wall. This study also found that if the slots were too large, flow through the wall could "anchor" the tow against the wall. The forces exerted on barge tows while anchored along the guard wall were measured. Wooley (1989) points out that tows, which are anchored against guard walls that are shorter than the tow, expose portions of the tow to crosscurrents and tend to rotate the tow around the upper end of the guard wall.

Design considerations of the upper lock approaches for the Arkansas River project were reported in U.S. Army Engineer Waterways Experiment Station (1963), Franco and McKellar (1966b), Franco and Shows (1968), Franco and McKellar (1968), Franco and McKellar (1969), Franco and Shows (1970), and Franco and Shows (1971). Generalization of these studies leads to the conclusion that guard walls should be ported in order to eliminate or reduce crosscurrents near the end of the wall. The ports should be sized to pass all of the flow the wall tends to intercept. This helps eliminate strong crosscurrents near the end of the wall and reduce the deep scour near the end and just downstream of the end of the wall (Franco and McKellar 1968). Properly sized ports in the upper guard wall eliminate or reduce crosscurrents near the end of the wall, which improves the movement of downbound tows into the approach. A lock guard wall on the riverside of the lock would produce navigation conditions considerably better than would a guide wall on the landside. With the latter wall, downbound tows would experience considerable difficulty in approaching the wall and in becoming aligned for entrance into the lock (Franco and McKellar 1966a). Wooley (1997a) determined that for lock and dam 3 on the Red River, hazardous crosscurrents existed near the bank upstream of the project, making the effective approach width larger than the 25.6-m (84-ft) lock width. This would explain why $\Sigma A_p/A_x$ had to be so large ($\Sigma A_p/A_x = 1.6$ at 1,700 cm/s (60,000 cfs)) for the recommended design. Shows and Franco (1978b) recommended for the Aberdeen lock and dam, Tombigbee River, that the lock approach be deepened and that a dike be constructed that would form an extension to the upper guard wall. These modifications reduced the crosscurrents at the end of the upper guard wall.

The Hannibal lock and dam, Ohio River, required ports in the upper guard wall to eliminate the crosscurrents near the end of the wall (Franco and Glover 1967). The study determined that the capacity of the ports should be sufficient to

pass all of the flow that the wall tends to intercept. Lowering the tops of the ports reduced the tendency for tows to be moved toward the guard wall and facilitated the movement of tows maneuvering for the approach to the auxiliary lock.

Research in support of the Greenup lock and dam, Ohio River (U.S. Army Engineer Waterways Experiment Station 1958) concluded that ports are required in the guard wall to reduce the intensity and abrupt change in alignment of currents sweeping around the end of the upper guard wall. The ease with which a tow can be made to drift into the upper approach to the locks is a function of the flow through the ports increases with the number or size of ports. Velocity in the upper approach and the accumulation of ice and drift increases with the number and size of ports.

Franco (1976) points out that projects in which the upper guard wall consists of pontoons and cells, tows can be made to drift into the upper approach with less difficulty, but because of the higher velocities, the tow tends to hit the guard wall with considerable force and can be in danger of hitting the lock gates. Also, the large amount of flow under the pontoons tends to pull tows against the guard wall and creates difficulties for tows approaching the auxiliary lock.

Skirts can be placed on the bottom of the pontoons. Those placed on the landside are more effective at reducing the draw toward the wall than the same length of skirt on the riverside. However, pontoons with skirts on one edge are subjected to a torque along the longitudinal axis by the force of the current. U.S. Army Corps of Engineers (1952) describes the earliest attempts at measuring forces exerted on a barge tow anchored along a guard wall. These results are presented in a plot of force exerted on a tow drafted at 2.74 m (9 ft) as a function of the elevation of the wall bottom. As expected, deeper wall depths resulted in lesser lateral forces on the anchored tow.

Research regarding Monongahela River projects is reported by Franco and McKellar (1966a) for lock and dam 4 and by Wooley (1997d) for Point Marion. Franco and McKellar (1966a) found that increasing the width of a lock places the upper guard wall riverward of the existing wall where it would tend to intercept a larger portion of the total river flow. This in turn, increases the crosscurrents near the end of the wall. These crosscurrents can be reduced or eliminated by the installation of ports in the guard wall. The minimum capacity of ports was not investigated. However, decreasing the capacity of the ports tends to reduce velocities in the upper lock approach and facilitates the movement of downbound tows approaching the landside lock. Wooley (1997d) determined that ports with sufficient capacity to pass most of the intercepted flow are required in the upper guard wall to the Point Marion project to eliminate the crosscurrents near the end of the wall and to facilitate the movement of downbound tows into the lock chamber. Wooley (1997d) recommended a multicelled wall with $\Sigma A_p/A_x = 1.1$. Franco and McKellar (1965), Franco and Shows (1967a, b), Franco and Glover (1967), U.S. Army Corps of Engineers (1958) all determined that the capacity of the ports should be sufficient to pass all of the flow that the wall tends to intercept.

Similar conclusions were reached as a result of Mississippi River studies. Shows and Franco (1979b) found that existing conditions on lock and dam 3, Mississippi River, had serious crosscurrents in the approach to the lock guide wall (landside). Because of these crosscurrents, navigation conditions for downbound tows approaching the lock were hazardous, particularly during higher flows. Navigation conditions in the upper lock approach investigated in the model study were made considerably better with a guard wall (riverside of the lock) in place of the guide wall. Shows and Franco (1979c) in the lock and dam 26, Mississippi River, study determined that during high flows, navigation conditions at the existing locks could be hazardous because of the alignment of the currents moving across the approach to the lock toward the spillway. Franco and Shows (1977) found that at the Columbus lock and dam on the Tombigbee River, navigation conditions in the upper approach tended to be hazardous because of the crosscurrents from the Tibee River tributary. This tributary crossed the navigation channel just upstream of the lock. Realignment of the tributary reduced the crosscurrents and provided safe navigation conditions.

Additional features

Additional features such as submerged dikes and revetment modifications are sometimes required to achieve safe navigation conditions in the upper approach. These features help reduce crosscurrents that create difficult navigation conditions for downbound tows approaching the lock. The channel alignment upstream of the upper approach to the lock can have a significant impact on navigation conditions for downbound tows approaching the lock. Realignment and excavation can be incorporated with submerged dikes to improve the conditions and reduce velocities to help provide safe navigation conditions. Wooley (1989) reports that submerged dikes can play an important role in the accomplishments of safe navigation conditions in conjunction with ported guard walls. Dikes can be used to increase or decrease outdraft at a particular ported guard wall configuration. Franco and Shows (1967b) improved the navigation conditions on the Millers Ferry lock and dam, Alabama River, by constructing a dike, which eliminated the currents moving across the channel.

Ice and debris passage gates

The model study of the navigation conditions at lock and dam 25, Mississippi River (Wooley 1997c), included evaluation of a guard wall opening constructed to pass ice and/or debris that had entered the upper lock approach. The ice passage opening provided good transport for ice and debris. Shows and Franco (1979b) found that flow through an ice gap has little effect on tows, but that it can be hazardous for small boats. Therefore, they recommend that a closure or barrier be placed in the gap when not passing ice and debris.

Shows and Franco (1979c) found that for lock and dam 26, Mississippi River, spillway gates were required between the locks with lock separation to eliminate serious crosscurrents in the lock approaches. However, this design must be coordinated with the two culvert lock filling and emptying system design so that one outlet is not located in spilling flow and the other in a quiescent pool.

The difference in water levels at the outlets produces a residual current through the lock culvert system (Davis and Davidson 1991).

Shows and Franco (1979a) found that a deeper approach channel reduced currents and thereby increased steerage capability in the John H. Overton, Red River, study. They report that satisfactory navigation conditions in the upper lock approach were gained by additional excavation of the approach channel and an increase in the length of the upper guard wall from a 198-m (650-ft) to a 229-m (750-ft) ported guard wall. Franco (1976) recommended that the upper guard wall, when used as a guide wall, should generally be as long as the clear portion of the lock chamber. Once the tow is behind the wall, it is safe from the effects of currents that would otherwise move the tow toward the spillway.

General design guidance

Observations and general design guidance gathered from the literature review are presented as follows:

a. Solid walls

    (1) A solid upper guard wall causes crosscurrents near the end of the wall.

    (2) Crosscurrents tend to move the head of downbound tows riverward and put them in danger of hitting the end of the wall.

    (3) There is a tendency for an eddy to form between the guard wall and the adjacent bank, producing a riverward current near the upstream end of the wall and a landward current some distance downstream.

    (4) Downbound tows must reduce speed as they approach the end of the wall, thus losing steerageway and the ability to overcome the effects of currents.

    (5) The strength of the crosscurrents depends on the amount of flow the guard wall tends to intercept.

    (6) Upper guard walls are generally straight, especially when the lock is adjacent to the spillway.

    (7) Flaring of the guard wall increases the amount of flow the wall intercepts and can affect the distribution of flow through the spillway.

b. Ported walls

    (1) Crosscurrents near the end of the guard wall can be altered with a ported guard wall.

    (2) Properly designed ports in the upper guard wall can reduce or eliminate crosscurrents near the end of the wall by permitting all or a major portion of the flow intercepted by the wall to pass under the wall.

(3) As a general rule, the total cross-sectional area of the port openings should be equivalent to the total cross-sectional area of the approach channel affected by the locks and lock walls.

(4) Flow through the ports will tend to move a tow toward the wall, and excessive flow under the wall could make it difficult for tows to pull away from the wall.

(5) The ratio of the ported area to the intercepted area is a major factor in the performance of the guard wall.

Purpose and Scope

The objective of this research is to provide additional and improve existing guidance so that engineers can design lock approach guard walls that are safe and efficient to the users, while being cost-effective. The guidance available in EM 1110-2-1611 (Headquarters, U.S. Army Corps of Engineers 1980) and rule-of-thumb guidelines requires approach walls to be fairly long; which means the cost of implementing the approach walls can be substantial.

This report provides additional guidance for the hydraulic design of lock guard walls. The governing factors such as required guard wall length, and port area are identified. This information will be especially beneficial for the design and evaluation of future or retro-fit projects.

Approach

Both physical and numerical models were used to help research guard wall design and develop guidance for design. The literature review was used to assist in identifying pertinent design needs and to develop the testing and evaluation program. A physical model was constructed so that a detailed evaluation could be performed for selected guard wall designs. A numerical model was used to help rapidly evaluate numerous designs and identify the designs to refine in the physical model.

2 Upper Approach Guard Wall Design

Physical Model

A physical model was used to evaluate numerous alternative guard wall types while varying flow depth and velocity. Descriptions of geometric and hydraulic quantities used in the following discussion are reported in prototype values unless otherwise stated. This was considered more convenient since the results are intended for field applications.

Description

An undistorted 1:50-scale physical model was constructed in a laboratory flume (see Figure 3). The model flume was 60 m (200 ft) long by 17 m (55 ft) wide. The model reproduced a straight upper approach channel to the lock or locks, various upper guard wall designs, and a dam with a gated spillway. The gated spillway reproduced 10 gates 30.5 m (100 ft) wide and 8 gates 15.3 m (50 ft) wide. The channel was a compound trapezoidal channel as shown in Figure 4. The crest of the gated dam was established as elevation 0. The elevation of the channel in the lock approach was 4.57 m (15 ft) with the area along the left descending bank being slightly higher at el 7.67 m (25 ft).

The model was built to allow modification of the lateral and longitudinal location of the locks and guard wall. This allowed testing of different intercepted flow areas as well as varying geometry with respect to the distance from the guard wall to the gated dam. The gated dam was placed in the model so that different gate operations could be performed and the impact of gate operation on guard wall performance could be evaluated.

A remote controlled model towboat was constructed to a 1:50 scale for use in developing tow tracks and interpreting guard wall performance. The model towboat is similar to a prototype towboat. The model tow has twin screws that operate in forward and reverse and are independent of one another. The model tow is also equipped with steering and flanking rudders.

Figure 3.   Laboratory model for lock approach research
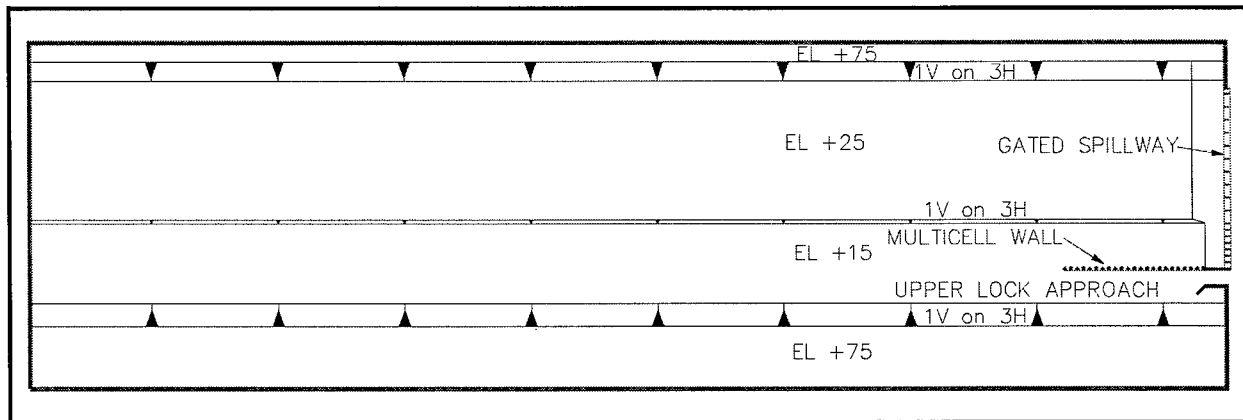
Figure 4.   Compound trapezoidal channel in laboratory model

Setting the model and prototype Froude numbers equal, results in the following relations between the dimensions and hydraulic quantities:

Characteristic	Dimension[1]	Scale Relation Model :Prototype
Length	$L_r = L$	1:50
Pressure	$P_r = L_r$	1:50
Area	$A_r = L_r^2$	1:2,500
Velocity	$V_r = L_r^{1/2}$	1:7.07
Discharge	$Q_r = L_r^{5/2}$	1:17,677.7
Time	$T_r = L_r^{1/2}$	1:7.07
Force	$F_r = L_r^3$	1:125,000
[1]Dimensions are in terms of length.		

These relations were used to transfer model data to prototype equivalents and vice versa.

Data gathering equipment

Various types of data are needed to evaluate guard wall performance. The different types of data collected include current direction and velocities, point velocities, tow tracks, and water surface elevations. Current direction and velocity data were obtained using a video tracking system that tracks cylindrical floats equipped with a light source. By systematically recording a video image of the floats at a given time interval, average current magnitude and direction can be computed. A track of float paths can be determined. This data allow for the comparison of current patterns and magnitudes for different guard wall types. Tow tracks were also collected using the video tracking system. Tow images, tow speed, and heading were computed and compared for the different guard wall designs.

Point velocity measurements were collected at 0.6 depth for the purpose of looking at flow distribution in the near field of the lock approach and to assist in the validation of the numerical model described in the next section. These point velocities were measured using two- and three-dimensional (2-D and 3-D) acoustic doppler velocity meters and a 2-D electromagnetic meter.

Water-surface profile data were obtained with piezometers and point gauges. The piezometers were located throughout the model and were connected to a centrally located gauge pit. These data are used to address longitudinal water-surface slopes as well as any lateral water-surface gradients across the channel.

Numerical Model

Purpose

The lock approach research required the development of a method to rapidly evaluate the navigation conditions in lock approaches for various guard wall configurations. The idea was to numerically model many guard wall configurations and then evaluate the most promising designs in the physical model with a remote controlled towboat. The approach was to select a numerical modeling technique and then evaluate the appropriateness of the model's use (validate) with comparisons to laboratory data. If the model adequately simulated the flow field produced by a guard wall, then various designs would be simulated in an attempt to gain general insight into the controlling features of guard walls. These simulation results could then be used to develop design ideas for further testing in the physical model.

Numerical model considerations

The choice of modeling method was important. The geometry of the guard wall dictates the flow patterns in the lock approach. The numerical flow model had to be designed so that only the geometrical parameters of the wall were changed from design to design and that the model would not rely on empirical coefficients. Empirical rules such as head-discharge relations rely on coefficients that can be dependent on the flow. For example, the discharge coefficient is sensitive to the direction of the flow relative to the control structure. Rather, a model was needed that relied on a physical description of the design to compute the flow passing under the guard wall.

The next consideration was the dimensionality of the model. Obviously, a one-dimensional description would not provide the lateral variability of the flow and so would not provide a means of estimating outdraft or draw toward the guard wall. A 2-D (depth-averaged) model would provide the lateral variations, but would have difficulty simulating flow under the guard wall. A 3-D model provides the best resolution of the physics. However, based on the available time and resources the 3-D model was not a viable means of evaluating a large number of design alternatives.

A compromise was reached wherein a 2-D (depth-averaged) model was used. The model HIVEL2D was extended to include lock walls. The lock walls were represented using a pressure field imposed on the water surface. This simulated a surface pressure head at the wall location equal to the depth of the wall penetration below the water surface. This modeling technique did not require any empiricism to describe the flow through the guard wall. The guard wall's port area set by the wall's cell spacing and wall depth controlled the volume of flow through the wall.

Validation

Validation of the numerical model was performed by comparing the results to the laboratory results. The comparisons were made with the type 5 design guard wall (366-m (1,200-ft) multicelled wall with a 9.1-m (30-ft) wall depth). Velocities at 0.6 depth resulting from a discharge of 3,550 cm/s (125,250 cfs) and a pool elevation of 12.8 m (42 ft) were measured at points on a 7.62-m (25-ft) spacing across the navigation channel. Navigation channel stations are shown in Figure 5. The computed velocities were compared with the measured values at eight stations along the navigation channel. The velocity distributions across the channel for each of the stations are shown in Figures 6-13. The model accurately reproduces the velocities at locations upstream of the guard wall (stations 4800, 2760, and 1920). However, the computed velocities were consistently less than those observed at the stations bounded by the guard wall (stations 1265, 1015, 765, 515, and 265). This error suggests that the computed volume of flow under the guard wall is less than that in the physical model. This underprediction of flow under the guard wall is attributed to the use of the hydrostatic pressure assumption. The hydrostatic pressure model neglects the vertical momentum as flow dives under the guard wall. Shallow water models underpredict the flow rate under adverse pressure gradients (Berger and Stockstill 1994) such as those present near the wall.
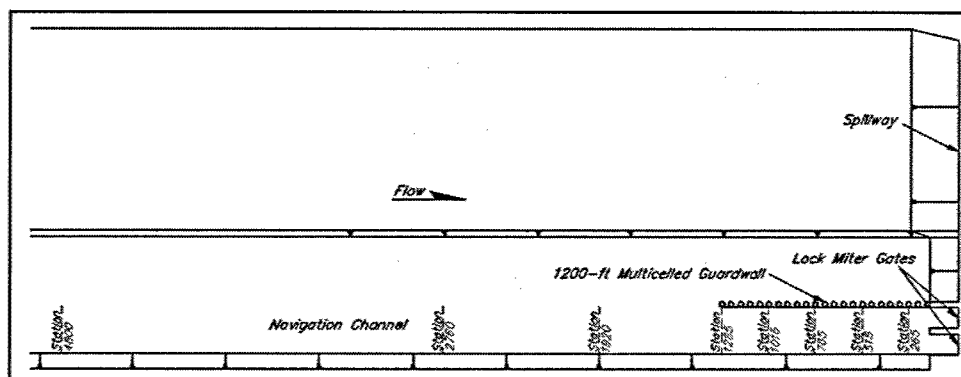
Figure 5. Location of stations along navigation channel

Adjustment of the wall draft would perhaps produce more accurate velocity predictions, but rather than developing rules pertaining to guard wall modeling, the research focused on the comparative differences computed for flow fields generated from one design versus another. The numerical model overpredicted outdraft, but underpredicted draw and should serve as a practical tool for screening design ideas.

Although steady boundary conditions were specified, the wall configurations and adjacent spillway produced unsteady flow solutions. Eddies formed and shed from the end of the guard wall and an unstable eddy moved about within the area between the wall and the bank. The periods of these flow evolutions were design dependent. Therefore, comparisons between various designs required time averaging. The model results presented are time averages of 8-hr simulations for the results shown in Figures 6-13 and everything presented hereafter.

Evaluation of Navigation Conditions

Navigation conditions in the physical model were evaluated for three types of guard walls (single multicell, floating, and long span) at two intercepted cross-sectional areas (about 91 m (300 ft) wide and 168 m (550 ft) wide). More than 30 simulations with varying designs were performed using the numerical model. Port heights, intercepted cross-sectional area, and wall length were varied to determine the effect of each on wall performance. Previous research indicated the major characteristic that would change the guard wall performance was the elevation of the top of the ports and the intercepted cross-section area of the guard wall.

Figure 6.   Velocity distribution across navigation channel, sta 4800

Figure 7.   Velocity distribution across navigation channel, sta 2760

Figure 8.   Velocity distribution across navigation channel, sta 1920

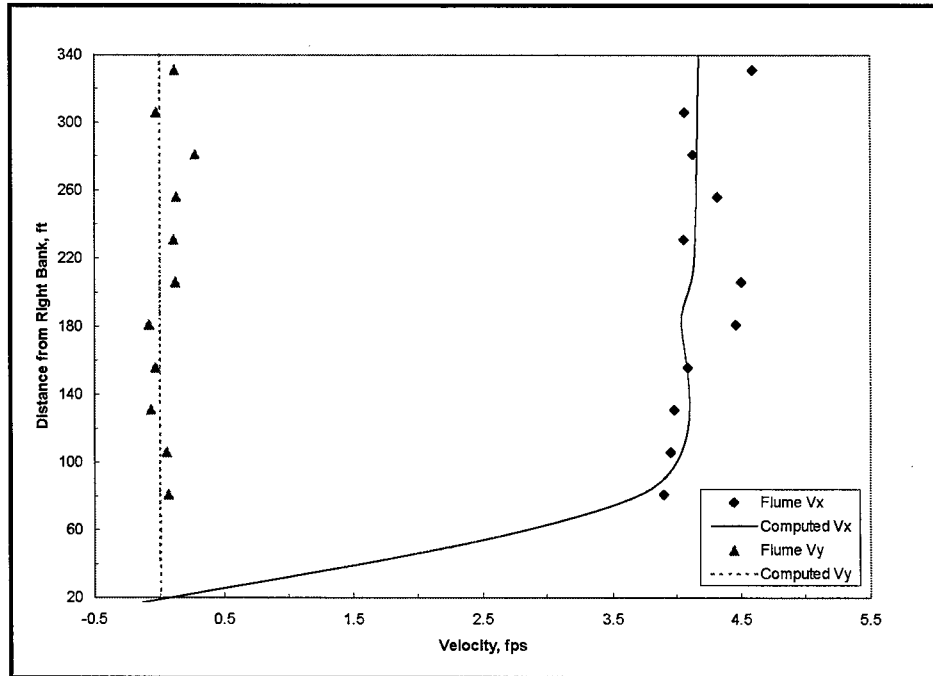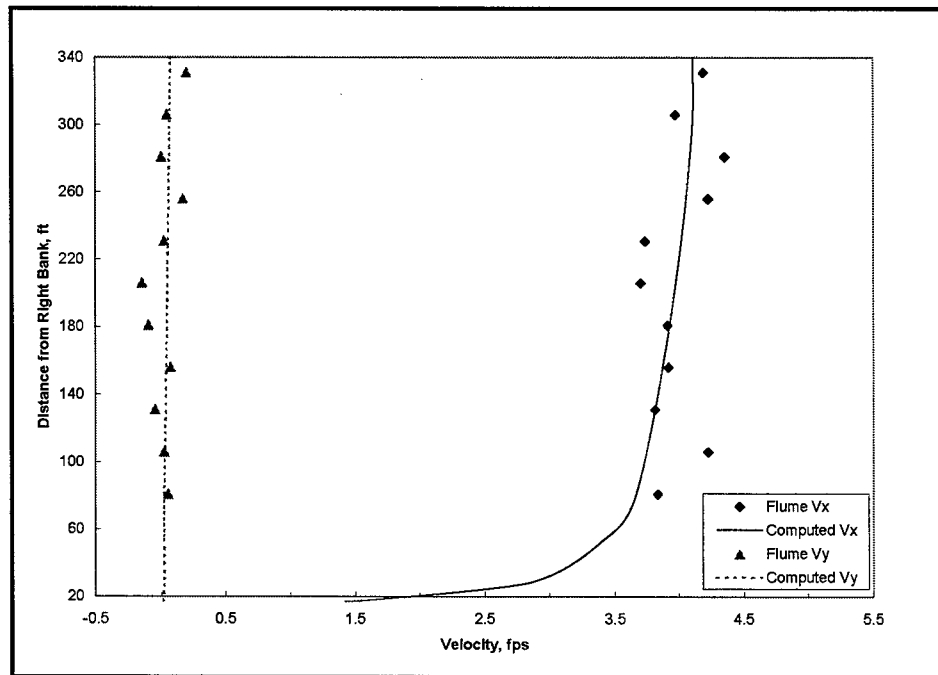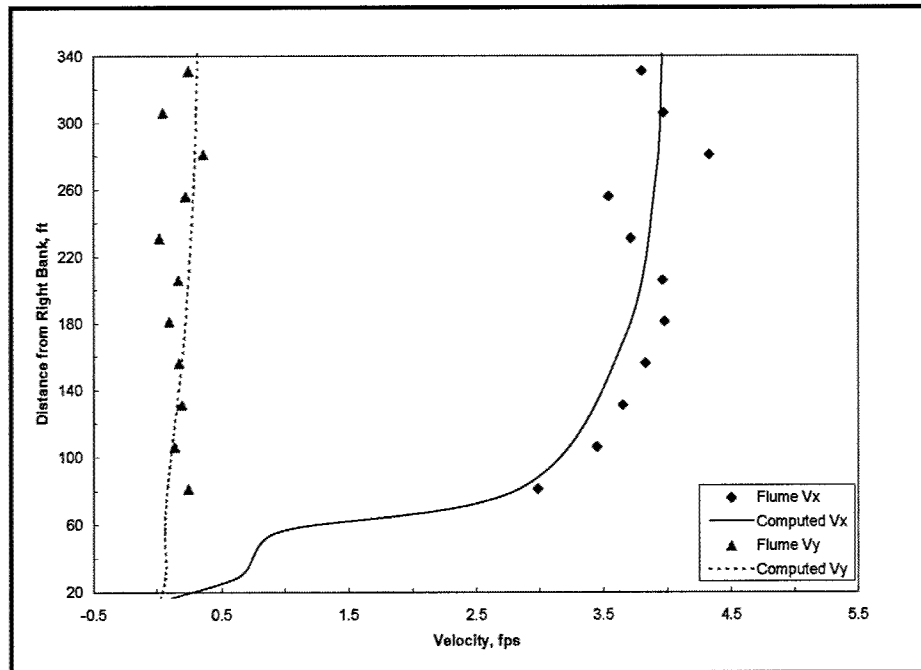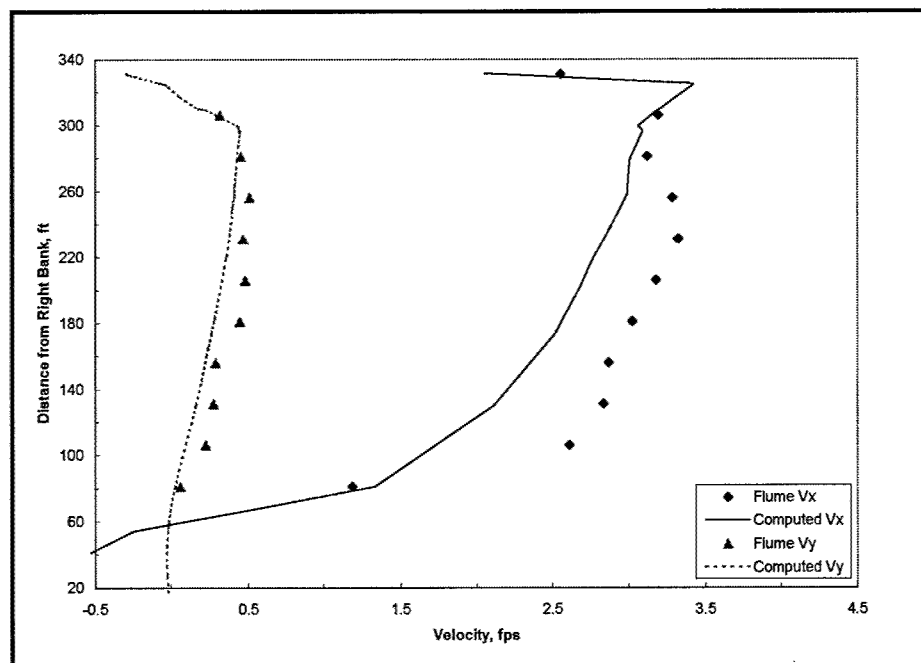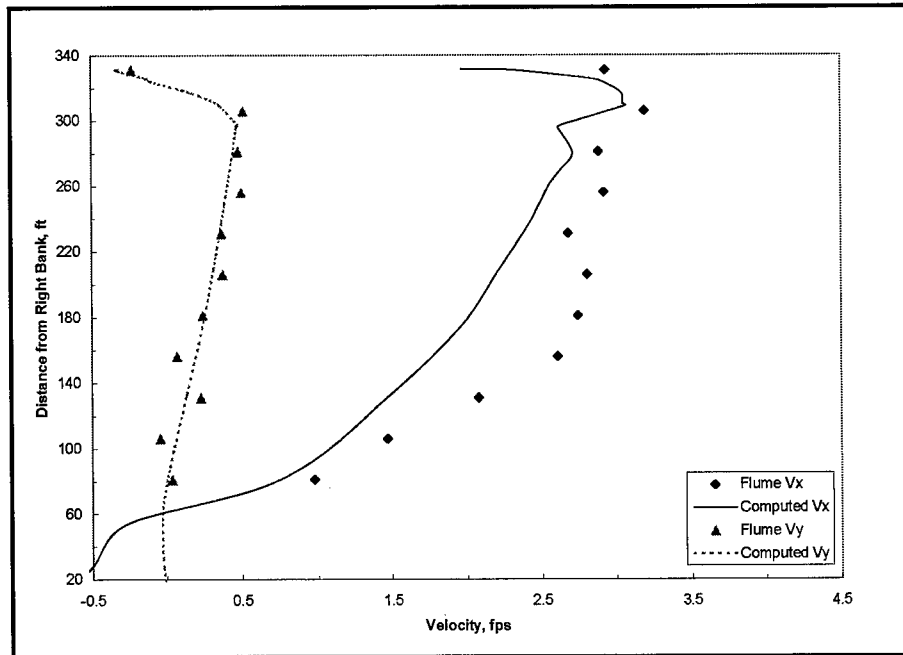Figure 9.   Velocity distribution across navigation channel, sta 1265

Figure 10. Velocity distribution across navigation channel, sta 1015
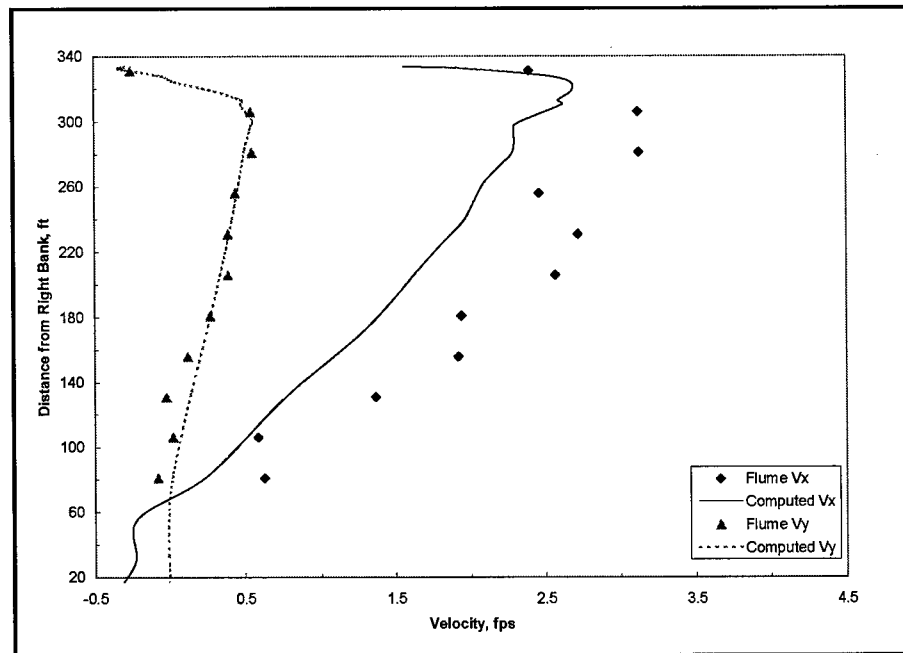
Figure 11. Velocity distribution across navigation channel, sta 765
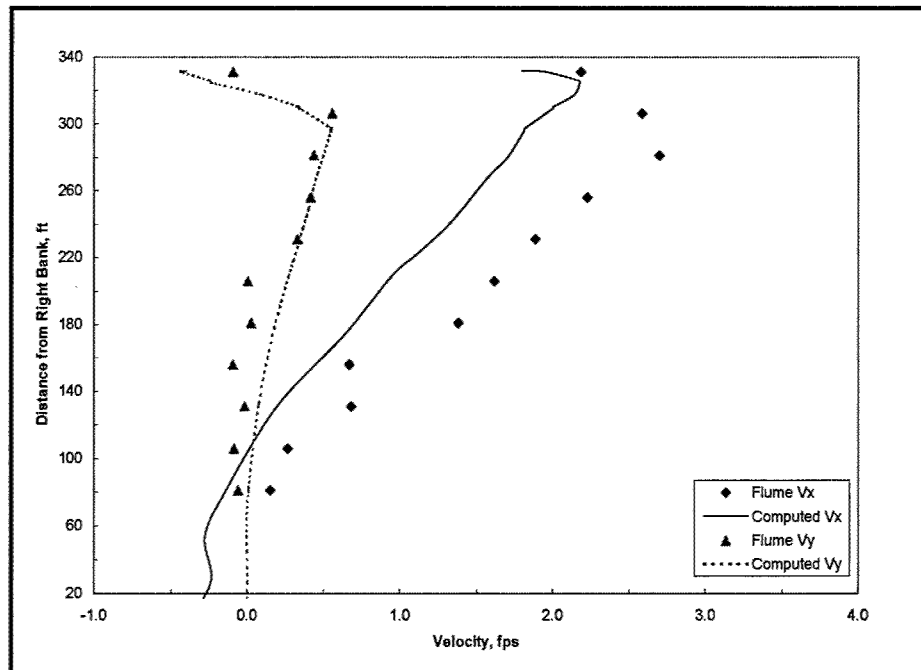
Figure 12. Velocity distribution across navigation channel, sta 515
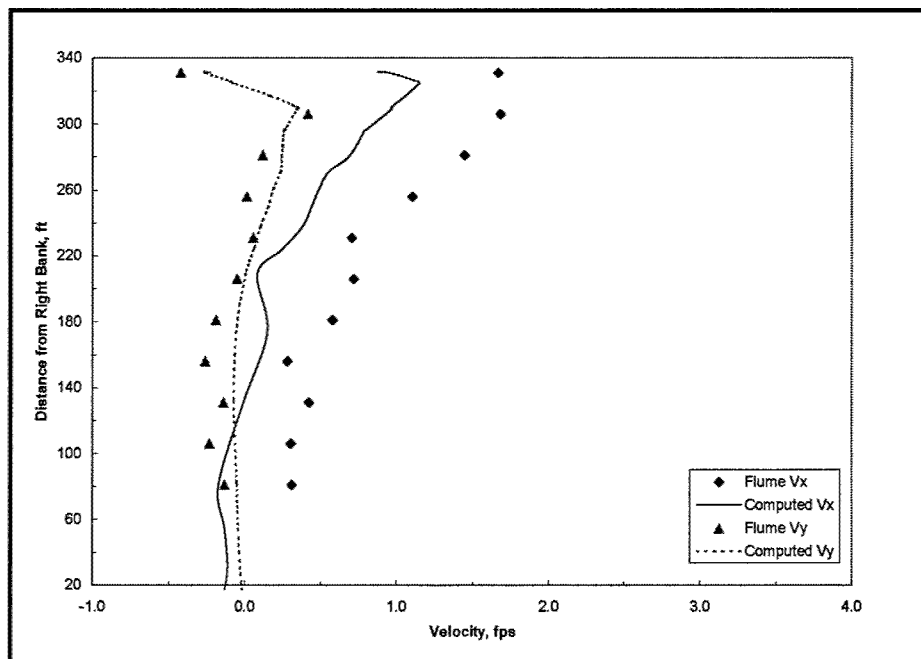
Figure 13. Velocity distribution across navigation channel, sta 265

Chapter 2   Upper Approach Guard Wall Design

Existing design guidance

In determining what channel configurations to use in testing the effects of guard wall geometry, some guidance was needed. A rule-of-thumb guideline for approach angles to the lock was used. A rule-of-thumb practiced over the years indicates that there should be an allowance for misalignment with the lock of at least 12 to 15 deg. Determination of approach geometry, first requires an appropriate approach width for the design size tow for the lock chamber. Using the rule-of-thumb guideline of an approach angle to the lock of 12 to 15 deg, the approach width can be determined as shown in Figure 14. This method revealed that a minimum approach width for the initial test conditions should be set at 91 m (300 ft).

$$AW = \sin(\Phi)*(TL + L1)$$

where
L1 = BW / tan (Φ)
Φ = maximum approach angle (12 to 15 deg)
BW = width of tow
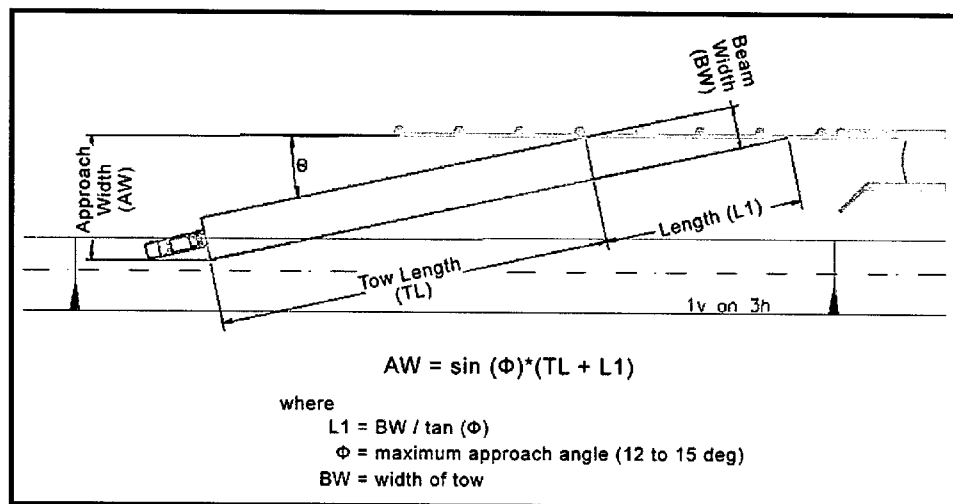
Figure 14. Determining approach width (AW)

Solid guard wall evaluation

Type 2 guard wall. To provide a "base" condition example for comparison, a solid guard wall was constructed in the physical model. The type 2 guard wall was nominally 366 m (1,200 ft) long with 8.5-m (28-ft) diam cells spaced on 15.2-m (50-ft) centers. The approach width with the type 2 guard wall was 91.4 m (300 ft). The type 2 guard wall was a solid guard wall that allowed no flow to pass under the guard wall. Therefore, the entire intercepted flow area moves toward the river channel upstream of the lock approach. Pertinent data for the type 2 guard wall and the subsequent designs evaluated are shown in Table 1.

Current direction and velocity (CDV) data were collected for a total river discharge of 3,170 m³/s (112,000 cfs). This discharge with a pool elevation of 42 (12.8 m) created approach velocities in the range of 0.9 to 1.2 m/s (3.0 to 4.0 fps). The currents in the upper approach to the lock were basically parallel to the right descending bank. As anticipated, significant outdraft was observed beginning about 150 m (500 ft) upstream of the end of the guard wall. The magnitude ranged from about 0.46 m/s to 1.07 m/s (1.5 fps to 3.5 fps). The angle

Table 1
Design Information for Guard Walls Evaluated

Design	Approach Width, ft[1]	Wall Type	Wall Length, ft	EL of Bottom (Curtain), ft	Under-wall Area-to-Cross-Section Area Ratio (Pool 42.0)
Type 2	250	Solid	1,200	NA	0.0
Type 3	250	Multicell	1,200	40	1.5
Type 4	250	Multicell	1,200	30	0.9
Type 5	250	Multicell	1,200	25	0.6
Type 6	250	Multicell	900	25	0.4
Type 7	250	Multicell	900	30	0.6
Type 8	250	Multicell	900	40	1.1
Type 9	250	Floating	1,200	40	3.3
Type 10	250	Floating	1,200	30	2.0
Type 11	250	Floating	1,200	25	1.3
Type 12	250	Floating	900	25	0.9
Type 13	250	Floating	900	30	1.4
Type 14	250	Floating	900	40	2.4
Type 15	250	Floating	1,200	20	0.7
Type 16	500	Multicell	1,200	40	0.8
Type 17	500	Multicell	1,200	30	0.5
Type 18	500	Multicell	1,200	25	0.3
Type 19	500	Floating	1,200	40	1.8
Type 20	500	Floating	1,200	30	1.1
Type 21	500	Floating	1,200	25	0.7
Type 22	500	Multicell	900	40	0.6
Type 23	500	Multicell	900	30	0.4
Type 24	500	Multicell	900	25	0.2
Type 25	500	Floating	900	40	1.3
Type 26	500	Floating	900	30	0.8
Type 27	500	Floating	900	25	0.5
Type 28	500	Combined	2,400	30	X
Type 29	250	Multicell - LS	1,200	25	1.1
Type 30	500	Multicell - LS	1,200	20	0.3
Type 31	500	Multicell - LS	1,200	23	0.5

[1] Units in this table are in feet. To convert to meters, multiply by 0.3048.

of the crosscurrent ranged from about 30 to 45 deg. Figure 15 shows the current directions and magnitudes as well as tow tracks obtained with the type 2 guard wall test.

Multicell guard walls

Several different configurations of multicell guard walls were examined in the physical model. Guard walls were modified in the physical model without any other model changes. The flow rates were held constant from one wall design to the next. The types 3-5 guard walls were all placed in the physical model for evaluation.

Type 3 guard wall. The Type 3 guard wall was nominally 366 m (1,200 ft) long with 8.5-m (28-ft) diam cells spaced at 15.2 m (50 ft) on center. The draft
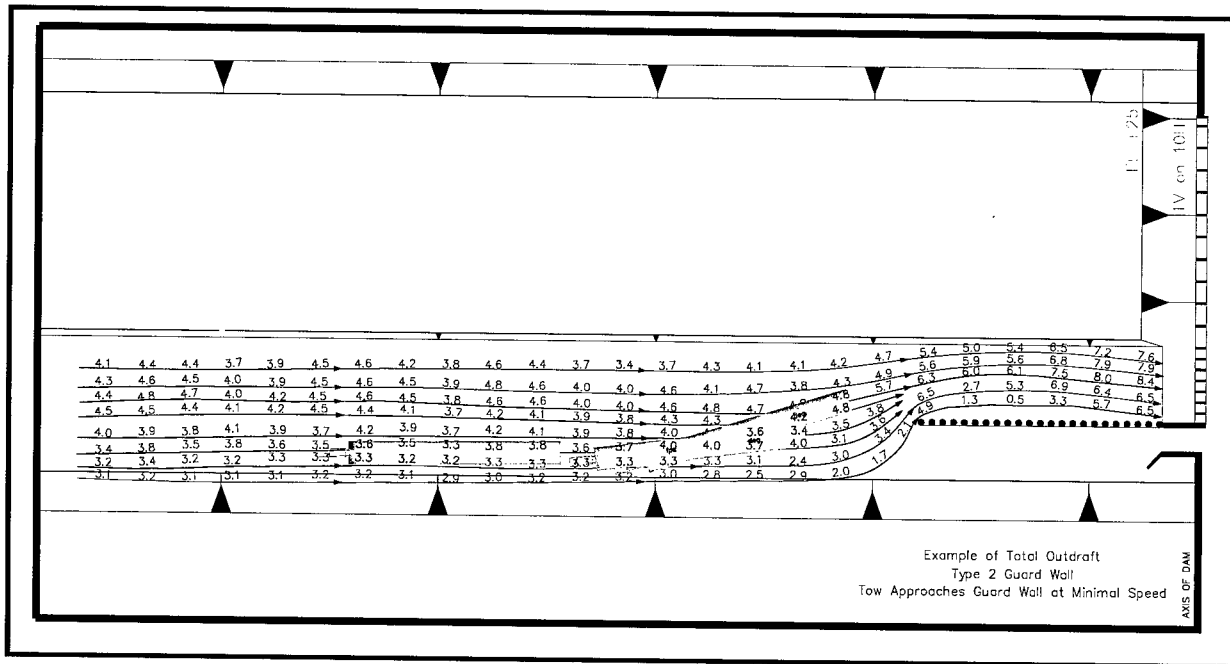
Figure 15. Total outdraft with type 2 guard wall

curtains were placed such that the bottom of the curtain was held at el 40 (12.2 m). This allows flow to pass under the guard wall providing a visual comparison of flow dispersion versus the type 2 wall. The ratio $\Sigma A_p/A_x$ was 1.5 with this design.

CDV data collected for a total river discharge of 3,170 m³/s (112,000 cfs) indicated that the currents in the upper approach to the lock were basically parallel to the right descending bank and the average magnitude ranged between 0.9 to 1.2 m/s (3.0 to 4.0 fps). As anticipated, the amount of crosscurrent in the 150 m (500 ft) directly upstream of the guard wall was significantly reduced compared with the crosscurrent produced with the type 2 guard wall. Also as expected, eddy currents existed just upstream of the lock. As a result of allowing current to flow into the lock approach and through the guard wall, outdraft forces were significantly reduced. However, due to the large port openings that result from relatively shallow drafted curtains, there is significant draw towards the wall. The 0.9-m/s (3.0-fps) magnitude of these currents, as well as the current direction and velocity and tow data, are shown in Figure 16. Draw towards the wall at this given magnitude of velocity produces greater than desirable impact on the guard wall. The angle of the current velocity is on the order of 11 deg.

Type 4 guard wall. The type 4 guard wall was nominally 366 m (1,200 ft) long with 8.5-m (28-ft) diam cells spaced at 15.2 m (50 ft) on center. For this wall, the draft curtains were placed such that the bottom of the curtain was held at el 30 (9.1 m). The ratio $\Sigma A_p/A_x$ was 0.9 with this design.

CDV data collected for a total river discharge of 112,000 cfs (3,170 m³/s) indicated that the currents in the upper approach to the lock were basically parallel to the right descending bank and the average magnitude ranged between 0.9 to 1.2 m/s (3.0 to 4.0 fps). As anticipated, the amount of crosscurrent in the 1,524 m (500 ft) directly upstream of the guard wall was significantly reduced
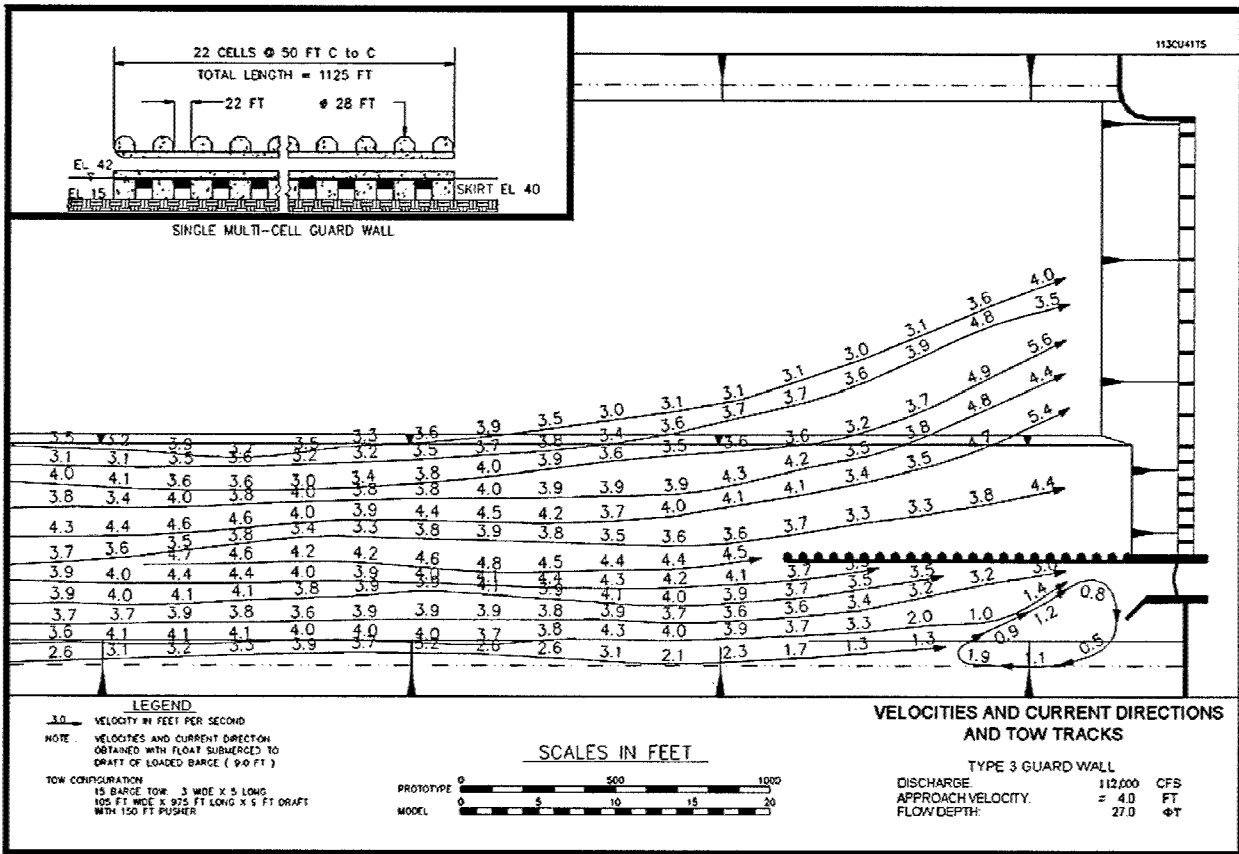
Figure 16. CDV and tow track data with type 3 guard wall

from the crosscurrent with the type 2 guard wall. Also as expected, eddy currents were visible just upstream of the lock. As a result of allowing current to flow into the lock approach and through the guard wall, outdraft forces were significantly reduced. At the same time, the deeper draft curtain elevation limited the amount of flow allowed under the wall as compared to the type 3 guard wall. Therefore, draw towards the wall was decreased as compared to the draw in the type 3 guard wall. The magnitude of these currents, as well as the current direction and velocity and tow data, are shown in Figure 17. The angle of the currents is on the order of 16 deg.

**Type 5 guard wall.** The type 5 guard wall was nominally 366 m (1,200 ft) long with 28-ft (8.5-m) diam cells spaced at 15.2 m (50 ft) on center. The bottom of the curtain was set at el 25 (7.6 m). This guard wall was similar to the type 4 guard wall except with less flow allowed to pass under the guard wall due to the lower draft curtains. The ratio $\Sigma A_p/A_x$ was 0.6 with this design.

Current direction and velocity data collected for a total river discharge of 3,170 m^3/s (112,000 cfs) are shown in Figure 18. The lower elevation of the draft curtains in the type 5 guard wall reduced the amount of flow into the lock approach and under the guard wall as compared to type 4 guard wall. The outdraft was more significant and lock approach entrance was more difficult due
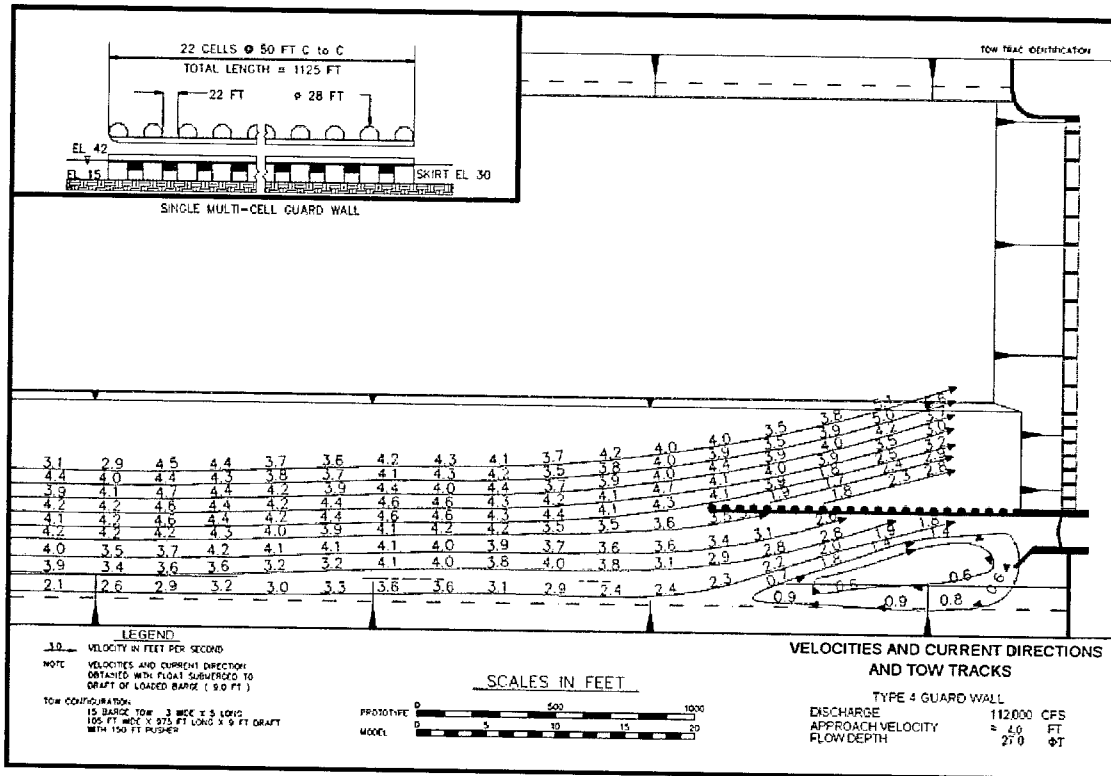
Figure 17. CDV and tow track data with type 4 guard wall

Figure 18. CDV and tow track data with type 5 guard wall

to the additional outdraft. Velocity magnitudes behind the guard wall were on the order of 0.6 m/s (2.0 fps) and approach the guard wall at an angle of roughly 17 deg.

Generalized numerical experiments

The numerical model was used next to evaluate designs. Several guard wall designs were evaluated to gain insight into the controlling geometric features of guard walls. These evaluations were intended to indicate the relative acceptability of various guard wall designs. The computed outdraft and draw towa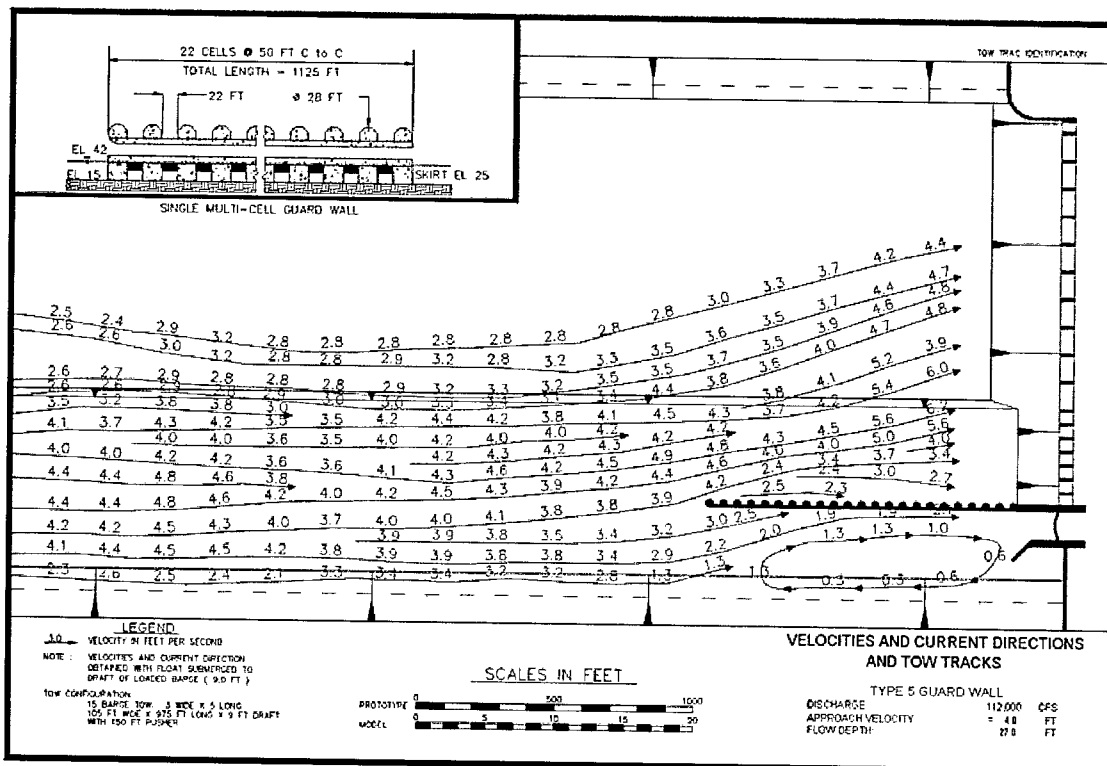rd the wall do not capture all of the forces acting on a tow, but rather serve as a means of ranking the designs on the basis of safe navigation conditions. Determination of the optimum navigation conditions is a balancing act between limiting outdraft, by providing more flow area under the wall, and limiting the draw toward the wall resulting from the under-wall flow. The draw toward the wall can cause the tow to strike the wall at an excessive speed and/or inhibit a tow resting on the wall from departing. Navigation conditions were evaluated based on water-surface slopes in the approach. Outdraft was estimated from the lateral gradients in water surface without consideration of vessel effects. A 3-wide by 5-long barge train drafted at 2.74 m (9 ft) was used in all the calculations. The reported outdraft was the maximum lateral force exerted on a body having the barge train dimensions whose location was varied from 3.3 tow lengths upstream of the lock to the end of the guard wall and at two sailing lines within the navigation channel. *Sailing Line A* placed the center of the middle barge 61.0 m (200 ft) landward from the landside of the guard wall and *Sailing Line B* placed the center of the middle barge 20.6 m (67.5 ft) landward from the landside of the guard wall. The sailing line remained parallel to the guard wall. The outdraft reach was considered the location along the sailing line beginning 3.3 tow lengths upstream from the end of the guard wall to the upstream end of the guard wall. As previously described, the numerical model was validated using the type 5 guard wall.

The draw toward the wall was determined for a 3 by 5 tow arrangement with the bow 0.2 tow lengths upstream of the lock and sitting 15.25 m (50 ft) or 0.5 tow widths away from the wall. Forces on the tow were approximated using the lateral water-surface gradients as was used in the outdraft calculations.

The types 2-5 guard walls were evaluated using the numerical model. The 366-m (1,200-ft) solid wall (type 2 guard wall) produced the flow field illustrated in Figure 19. The currents within the navigation channel upstream of the wall bend toward the main river. There is little flow between the land and the wall. A 366-m (1,200-ft) multicell wall (type 5 design) allows flow under the wall as shown in the vector plot on Figure 20.

A plot of flow distribution along the wall for various drafts (Figure 21) shows that as under-wall area-to-cross-sectional area decreases so that the flow control is at the under-wall area, the flow is more uniformly distributed along the wall. It is not suggested that uniform flow along the wall is required to have acceptable navigation conditions, but it does mean that flow concentrations that may accelerate the tow toward the wall are not present.
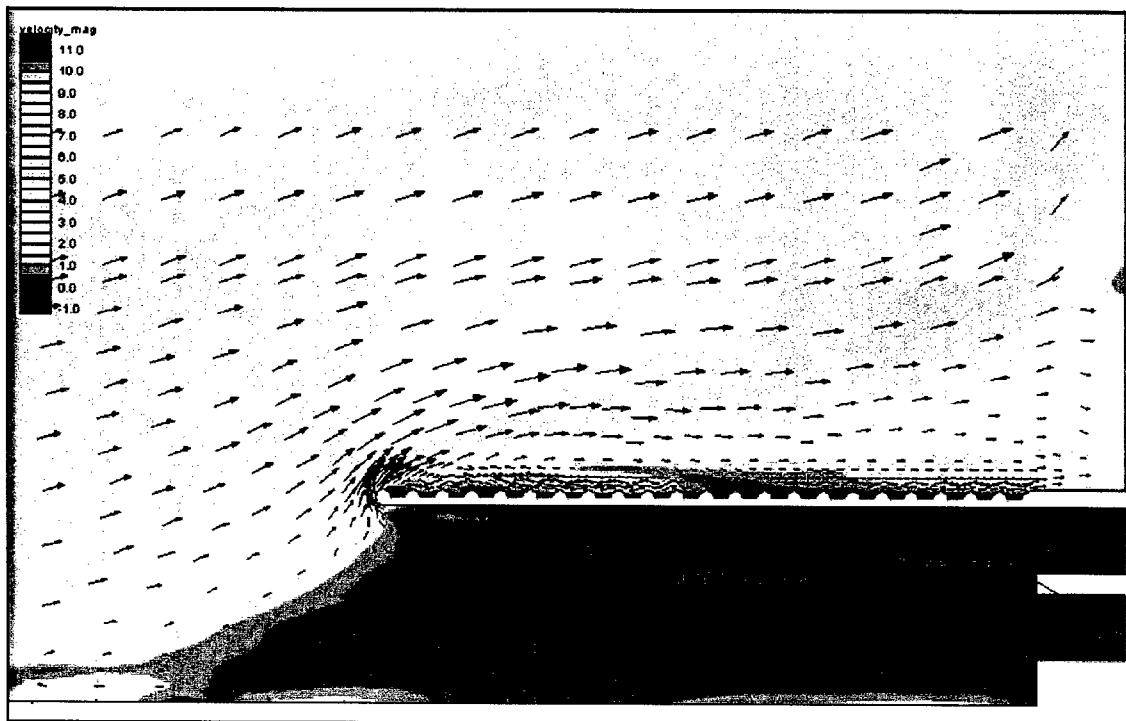
Figure 19. Type 2 guard wall, 366-m (1,200-ft) solid wall, velocity vectors and contours
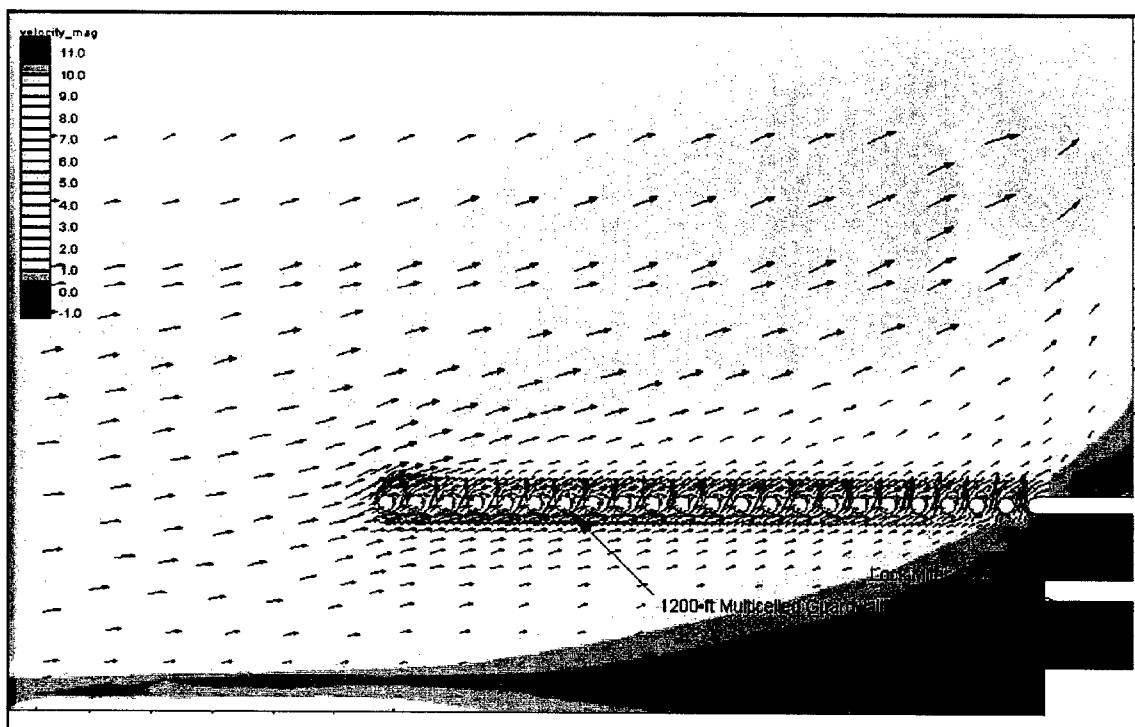
Figure 20. Type 5 guard wall, 366-m (1,200-ft) multicelled wall, draft curtain bottom at el 30, velocity vectors and contours
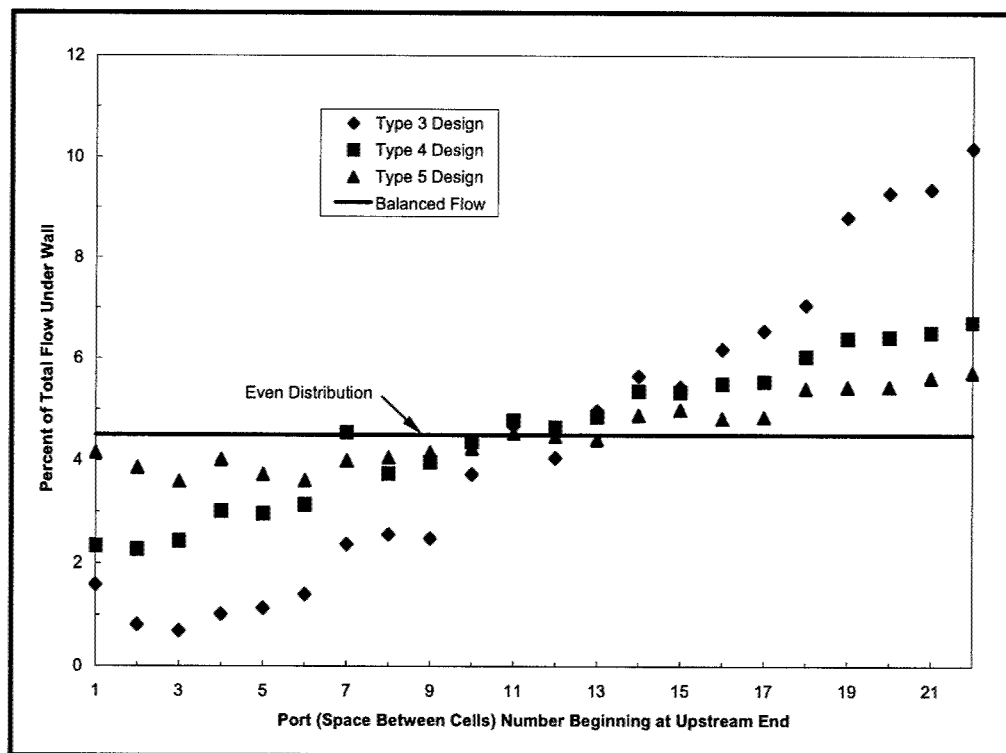
Figure 21. Flow distribution along multicelled wall

The estimated lateral forces computed from the numerical model results are shown in the bar chart provided in Figure 22. The forces computed with the types 2-5 guard walls are shown along with subsequent designs evaluated. The chart shows that designs such as the solid wall (type 2 guard wall) and others that have low under-wall flow area-to-cross-sectional areas produce large outdraft but negligible draw toward the wall. Designs that have a large port area such as the type 3 design guard wall (366-m (1,200-ft) multicelled with 0.61-m (2-ft) draft) have little outdraft, but extremely high draw toward the wall. This illustrates that an optimum guard wall design will have to balance outdraft and the draw toward the wall such as produced with the type 4 guard wall.

Types 6-8 guard walls. The types 6-8 guard walls were evaluated next numerically. Each of these walls was a multicell type nominally 900 ft (274 m) long with 8.5-m (28-ft) cells spaced at 15.2 m (50 ft) on center. The shorter wall will have a smaller total port area than the larger wall and if the intercepted flow area does not change with wall length the ratio $\Sigma A_p/A_x$ will be smaller. The elevation of the bottom of the curtain was varied with each design. The bottom elevation was at 25 (7.6 m) with the type 6 guard wall, 30 (9.1 m) with the type 7 guard wall, and 40 (12.2 m) with the type 8 guard wall. This provided $\Sigma A_p/A_x$ of 0.4, 0.6, and 1.1, respectively. A comparison of the forces between the 366- and 274-m- (1,200- and 900-ft-) walls with similar curtain elevations showed that the outdraft forces were higher due to the reduction in port area. The draw to the wall was also minimal with the type 6 guard wall. The ratio $\Sigma A_p/A_x$ was 0.4 with this design.
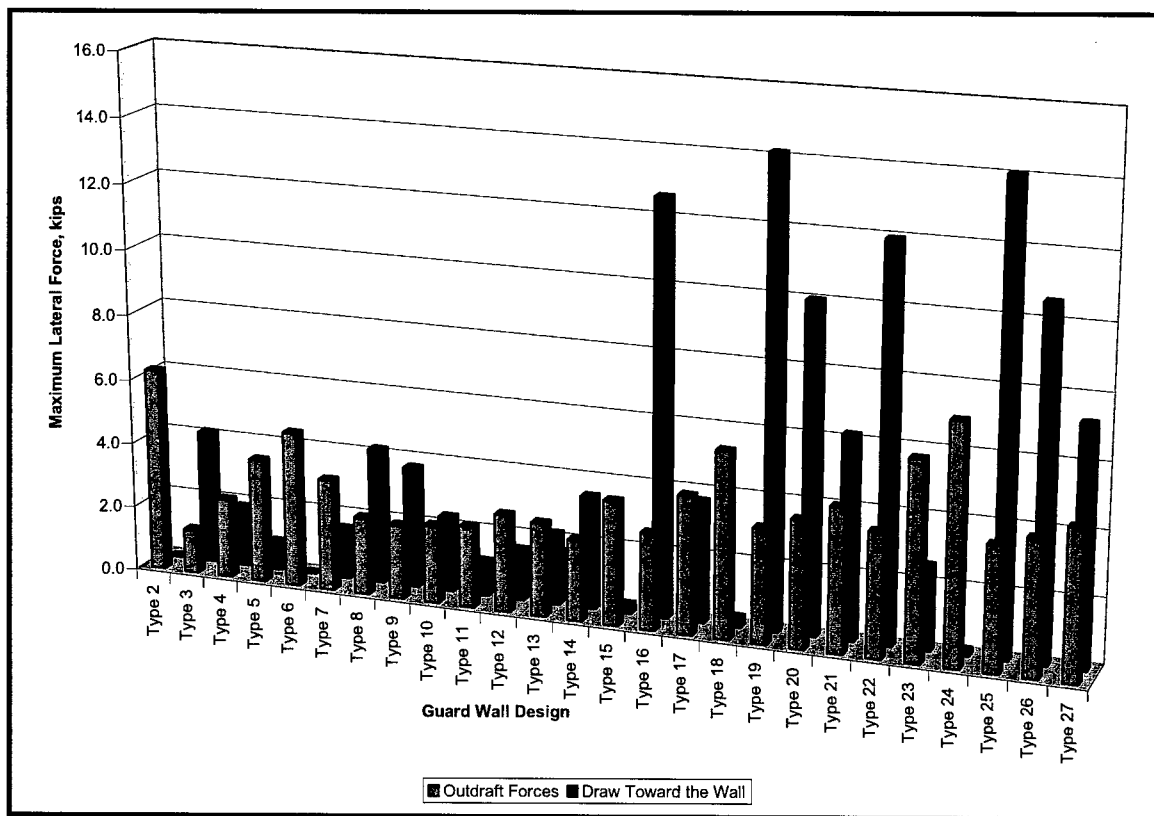
Figure 22. Comparisons of outdraft and draw toward guard wall

Floating guard walls

After completing the testing of the multicell guard walls, floating guard walls were evaluated. Based on the information gathered in the numerical model, the type 10 guard wall was constructed in the physical model.

Type 9 guard wall. The first floating wall design was evaluated numerically. The type 9 guard wall consisted of a 366-m- (1,200-ft-) long wall with the bottom of the wall at el 40 (12.2 m). This provided a $\Sigma A_p/A_x$ of 3.3. This ratio was considered large and the forces due to draw were about twice as large as the outdraft forces (Figure 22). The results indicated the bottom of the wall should be lower to reduce the draw.

Type 10 guard wall. Based on the results observed with the type 9 guard wall, the type 10 guard wall was constructed in the physical model. The type 10 guard wall was a 366-m- (1,200-ft-) long floating guard wall with the bottom of the draft curtains set at el 30 (9.1 m). The type 10 guard wall configuration yielded acceptable results based on tow maneuverability. CDV and tow track data measured with the type 10 guard wall are shown in Figure 23. The type 10 wall was also evaluated numerically and velocity vectors and contours from these calculations are shown in Figure 24. After evaluating the type 10 guard wall, it was determined that possibly lowering the curtain might improve guard wall performance.

Figure 23. Type 10 guard wall, 366-m (1,200-ft) floating wall, draft curtain bottom at el 30, velocity vectors and contours

Figure 24. CDV and tow track data with type 10A guard wall
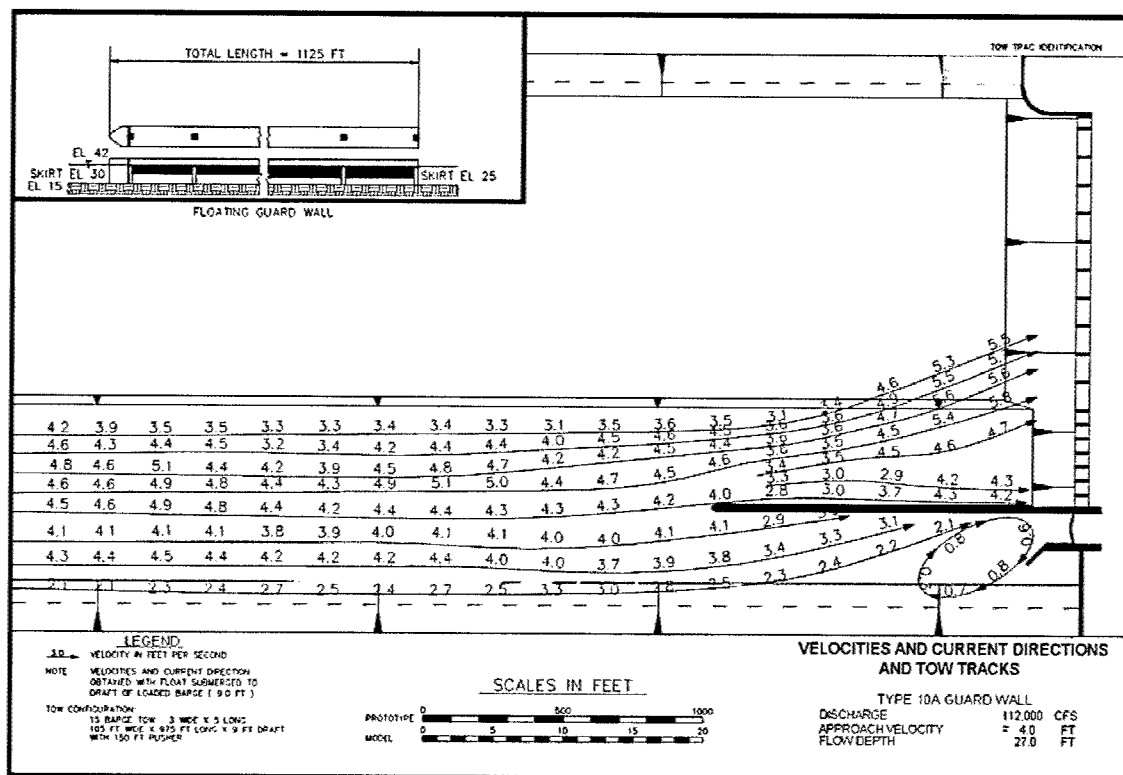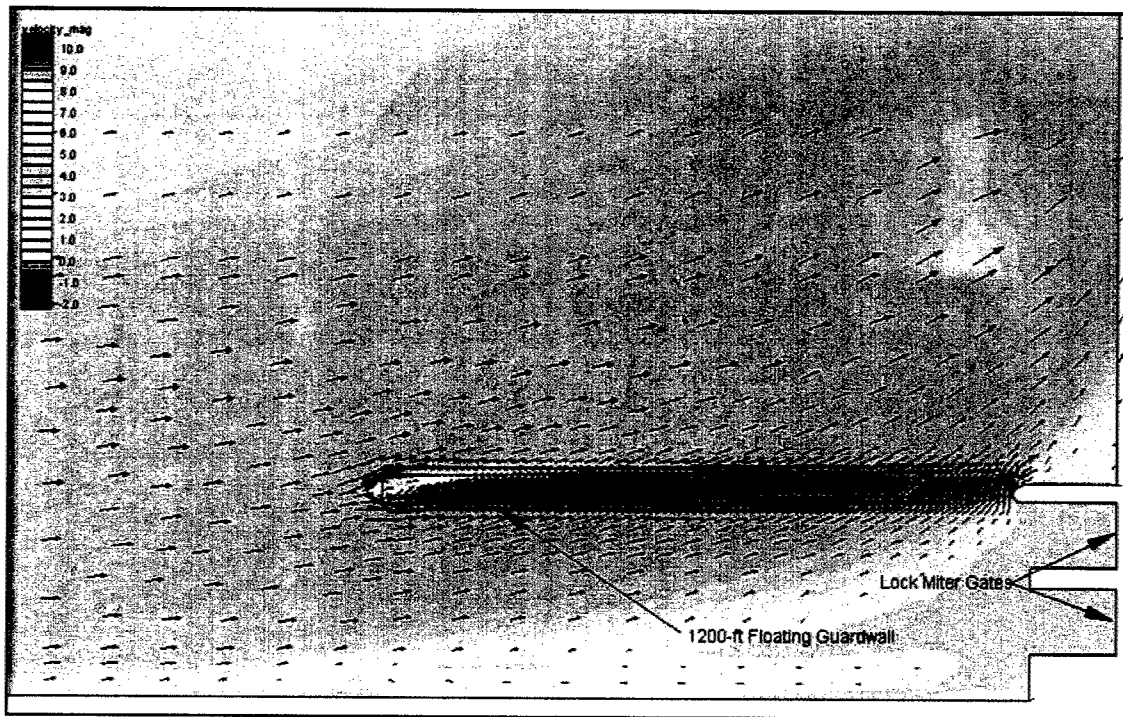
Type 10A guard wall. The type 10A guard wall was similar to the type 10 guard wall except the curtains were modified slightly in the physical model. The curtains were adjusted such that the upper two-thirds had curtains drafted to el 30 (9.1 m) while the lower one third had curtains drafted to el 25 (7.6 m). This modification was done in an attempt to reduce the outdraft observed with the type 10 guard wall.

Current direction and velocities were collected for a total river discharge of 3,170 m^3/s (112,000 cfs). These data are shown in Figure 24. The velocity magnitudes behind the guard wall were in the range of 0.61 to 1.15 m/s (2.0 to 3.8 fps) and approach the guard wall at an angle of approximately 12 deg. The low angle of approach aids the towboat in entering the lock approach and thus the lock at the proper angle. The eddy forming behind the guard wall appears to be small and is somewhat rotated normal to the direction of the flow. This guard wall geometry yields a positive entrance angle for the tow while keeping the velocities at an acceptable level, producing an efficient geometry. The ratio $\Sigma A_p/A_x$ was 1.7 with this design.

Type 11 guard wall. The Type 11 guard wall was evaluated numerically. The curtains were adjusted such that the bottom elevation was 25 (7.6 m) in an attempt to reduce outdraft and minimize draw towards the wall. The forces shown in Figure 22 indicate the balance between the outdraft and draw were not as good with the type 11 guard wall as was observed with the type 10 guard wall. The ratio $\Sigma A_p/A_x$ was 1.3 with this design and was too low for the floating walls.

Types 12-14 guard walls. The types 12-14 guard wall designs consisted of 900-ft- (274-m-) long floating walls with the bottom of the draft curtains set at el 25 (7.6 m), el 30 (9.1 m), and el 40 (12.2 m), respectively. These designs were evaluated numerically and the computed forces are shown in Figure 22. The type 13 design performed the best since the forces due outdraft and draw were nearly the same. The bottom of the draft curtain was at el 30 (9.1 m) with the type 13 guard wall.

Type 15 guard wall. Another 366-m- (1,200-ft-) long floating wall was evaluated numerically with the bottom of the curtain set at el 20 (6.1 m). This reduced the $\Sigma A_p/A_x$ to 0.7. The forces due to draw were the smallest of the 366-m (1,200-ft) floating wall designs. However, the outdraft forces were the largest as shown in Figure 22 by comparing the type 15 guard wall results with the types 9-11 guard wall results.

Wide approach widths

Tests to determine the effects of a wider approach width were performed next. The physical model was modified to reproduce a 150-m (500-ft) approach width. Similar guard wall configurations tested with the 90-m (300-ft) approach width in the physical model were tested with the 150-m (500-ft) approach width. A wider approach width increases the intercepted area (A_x) and if the ported area under the guard wall (ΣA_p) remains the same, the ratio of $\Sigma A_p/A_x$ will become smaller. A smaller ratio results in increased outdraft.

Types 16-18 guard walls. The wider approach widths tested with the 366-m- (1,200-ft-) long multicell walls were the types 16-18 guard walls. The bottoms of the draft curtains were set at el 40 (12.2 m), el 30 (9.1 m), and el 25 (7.6 m), respectively, with these designs. Forces due to outdraft and draw were computed from numerical results and are shown in Figure 22. Computed forces due to draw were excessive with the type 16 guard wall. The best design based on balanced forces was the type 17 guard wall. The draft curtain was at el 30 (9.1 m) with this design and the ratio of $\Sigma A_p/A_x$ was 0.5.

Types 19-21 guard walls. Floating walls were evaluated next with the wider approach width. The types 19-21 were 366-m- (1,200-ft-) long floating walls with the bottom of the draft curtains varied between elevations 40 (12.2 m) and 25 (7.6 m). Similar to the 366-m- (1,200-ft-) long multicell wall, the forces due to draw were excessive with the bottom of the curtain set at el 40 (12.2 m) (type 19 guard wall). The forces due to draw were higher than the forces due to outdraft for all three of these wall designs.

Types 22-24 guard walls. Multicell walls 274 m (900 ft) long were evaluated next. The bottoms of the draft curtains were set at el 40 (12.2 m), el 30 (9.1 m), and el 25 (7.6 m) for these designs. The forces due to draw were large with the type 22 guard wall. This design had the bottom of the draft curtains set at el 40 (12.2). The forces due to outdraft were higher than the forces due to draw with the types 23 and 24 guard walls.

Types 25-27 guard walls. The performance of floating walls 274 m (900 ft) long were evaluated with the bottom of the draft curtains set at el 40 (12.2 m), el 30 (9.1 m), and el 25 (7.6 m). The computed forces shown in Figure 22 indicate the outdraft and draw were almost the same as those with the 366-m (1,200-ft) floating walls. The 92-m (300-ft) difference in length did not significantly change the computed forces.

The increased outdraft was expected due to the increase in cross-sectional area of flow behind the guard wall. While the wider approach widths increased the available room for pilot maneuvering, the overall navigability of the lock approach was not necessarily improved. Larger forces were produced with wider approach (150-m (500-ft) width, types 16-27).

Type 28 guard wall. Many of the lock extension designs are proposing extending existing guide and guard walls using floating walls. The type 28 guard wall consisted of a 366-m (1,200-ft) floating guide wall on the landside of the lock and a 366-m (1,200-ft) multicell wall connected to a 366-m (1,200-ft) floating wall as the guard wall on the riverside of the lock. The design was not fully evaluated due to time constraints.

Long span guard walls

The long span multicell wall was considered a viable design to evaluate. The center to center spacing for the 8.5-m (28-ft) diam cells was 45.7 m (150 ft) for the long span compared to the 15.2 m (50 ft) spacing with the previous multicell walls evaluated.

Type 29 guard wall. The type 29 guard wall was nominally 366 m (1,200 ft) long with 8.5-m (28-ft) diam circular cells spaced at 45.7 m (150 ft) on center. This design was tested with an approach width of 90 m (300 ft) and the flow curtains were present along the length of the guard wall. The bottom of the four upstream curtains was set to el 30 (9.1 m) and the bottom of the four downstream curtains was set to el 25 (7.6 m).

CDV and tow track data were collected for a total river discharge of 3,170 m³/s (112, 000 cfs). The velocities upstream of the guard wall were generally parallel to the bank on the order of 1.2 m/s (4.0 fps). As the flow approached the nose of the wall, the current split into two paths, one leading towards the bank and the other towards the spillway. The currents towards the bank just upstream of the nose of the guard wall form an eddy just upstream of the lock chamber. The currents behind the guard wall approach the wall at an angle of approximately 15 deg and have a magnitude of approximately 0.91 m/s (3.0 fps). Due to the magnitude and angle of these velocities, the tow was pulled hard into the wall and impact was considered excessive. The current directions and velocities, as well as the path of the tow are shown in Figure 25.

Figure 25. CDV and tow track data with type 29 guard wall

Type 30 guard wall. The type 30 guard wall was tested next. This guard wall was nominally 427 m (1,400 ft) long with 28-ft (8.5-m) diam circular cells spaced at 45.7 m (150 ft) on center. Flow curtains were present along the length of the guard wall and were drafted to el 20 (6.1 m). The approach width was 168 m (550 ft).

CDV and tow track data were collected for a total river discharge of 3,170 m³/s (112, 000 cfs). The velocities upstream of the guard wall were parallel to the bank and on the order of 0.91 m/s (3.0 fps). A large eddy formed behind the guard wall and the currents sweep from the bank towards the wall. The currents behind the guard wall approached the wall at an angle of approximately 20 deg and the magnitude of the velocities was approximately 0.91 m/s (3.0 fps) in the upper approach. Due to the magnitude and angle of these velocities, the tow was pulled into the wall and impact was harder than desired. The current directions and velocities, as well as the path of the tow are shown in Figure 26.
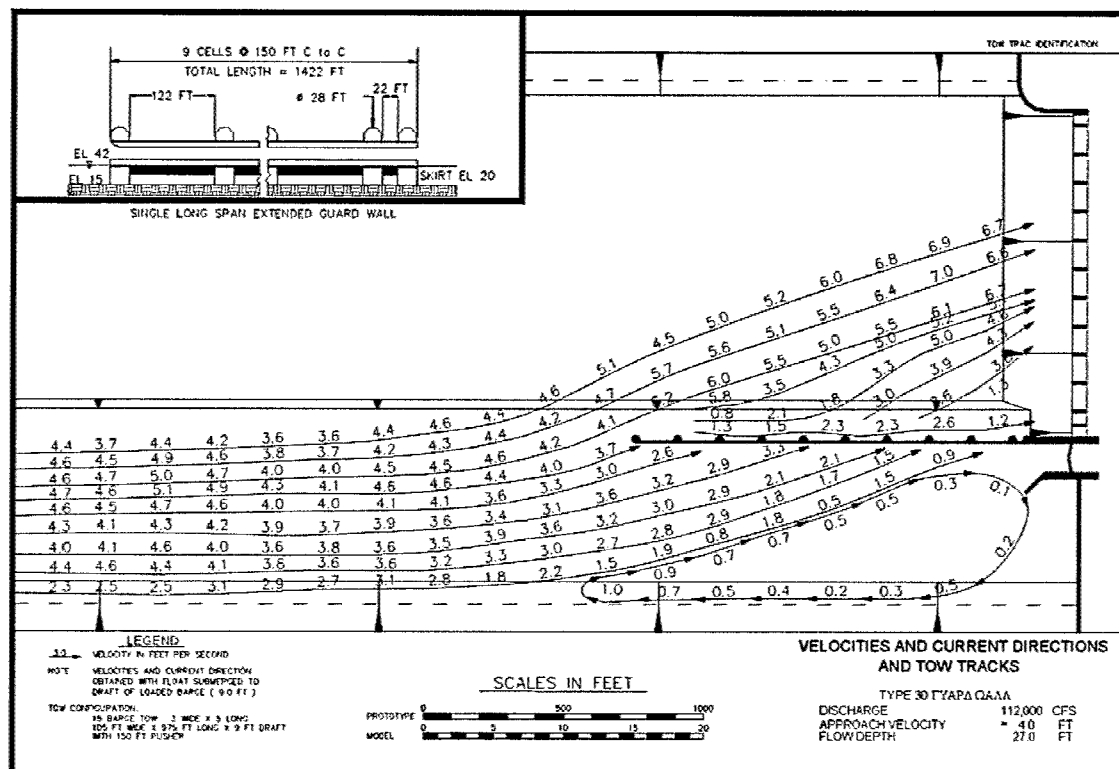

Figure 26. CDV and tow track data with type 30 guard wall

Type 31 guard wall. The type 31guard wall was nominally 488 m (1,600 ft) long with 8.5-m (28-ft) diam circular cells spaced at 15.2 m (50 ft) on center. Flow curtains were present along the length of the guard wall and were drafted at el 23 (7.0 m) to impede flow. The approach width was also 168 m (550 ft) with this design.

CDV and tow track data were collected for a total river discharge of 3,170 m³/s (112, 000 cfs). The data showed that velocities upstream of the guard wall were parallel to the bank and between 0.91 to 1.52 m/s (3.0 to 5.0 fps). An eddy formed behind the guard wall. The currents behind the guard wall approached the wall at an angle of approximately 17 deg and the magnitude of the velocities near the upper wall between the wall and the bank were approximately 0.91 m/s (3.0 fps). These velocities were slightly higher than those measured with the type 30 design. The higher skirt elevation with this design flattened the angle the currents approached the wall, which resulted in easier entrance into the approach

and a softer landing on the guard wall. The current directions and velocities, as well as the path of the tow are shown in Figure 27.
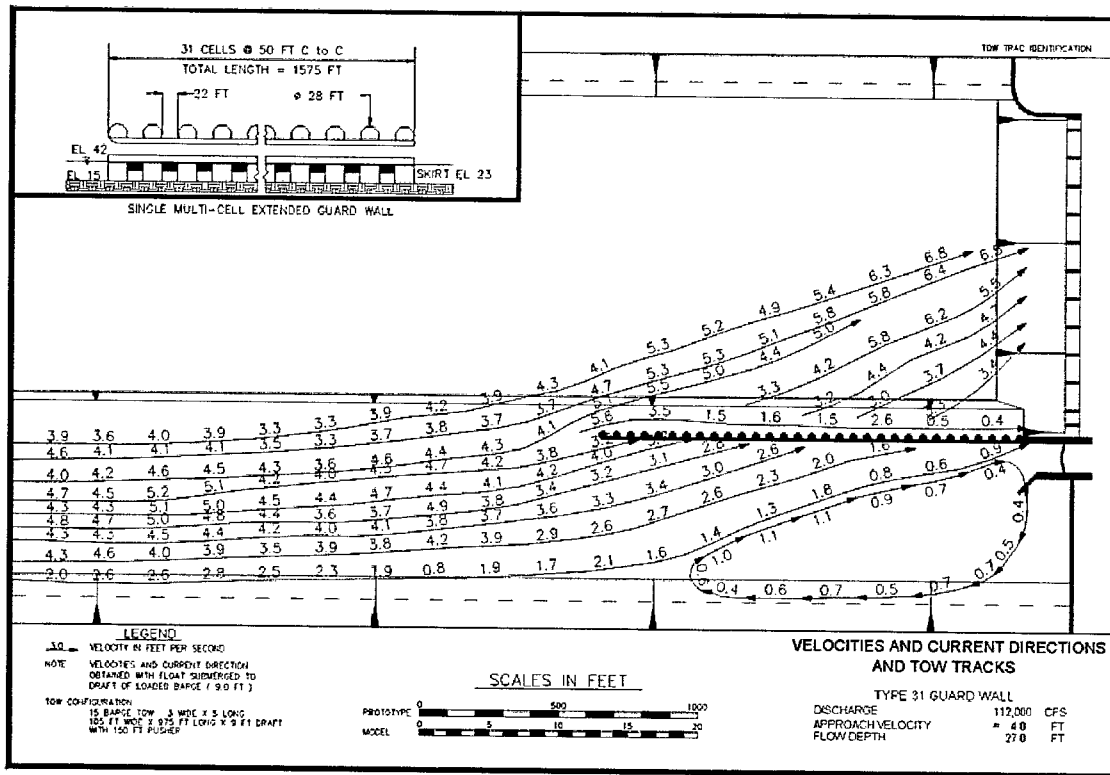

Figure 27. CDV and tow track data with type 31 guard wall

Summary of Results

The designs evaluated included a solid wall, multicell walls (short and long span), and floating walls. The testing of the guard wall configurations in both the physical and numerical models led to several significant revelations. First of all, the model data suggest that optimizing the ratio of the sum of the total port area in the guard wall to the sum of the intercepted cross-sectional flow would balance the outdraft and the draw towards the wall. Further, the data indicate that for each type wall, there will be unique values for the ratio of the sum of the total port area to the sum of the intercepted flow that provide the optimum geometric configuration.

Wall lengths were 366 m (1,200 ft) and 274 m (900 ft) single and the multi-cell and floating walls were evaluated for curtains having different drafts. A graph of forces as a function of wall flow area was constructed for the type 2-8 guard walls as shown in Figure 28. The type 2 guard wall was solid and is included with the data for types 3-5 for comparison. The solid wall produces the maximum outdraft. The forces computed with the 366-m (1,200-ft) multicell wall show that ratio $\Sigma A_p/A_x$ of just over 1.0 balances the forces due to outdraft
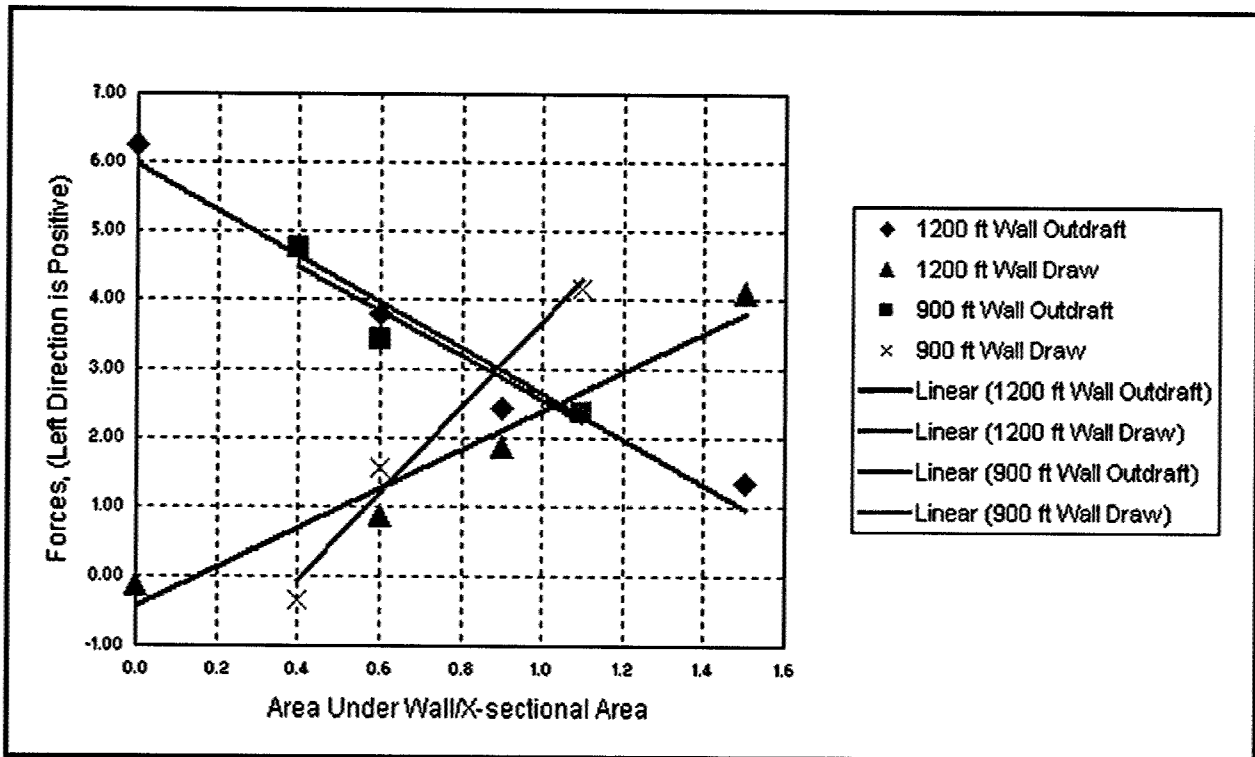
Figure 28. Computed forces with types 2-8 guard walls

and draw (i.e., the location where the blue and orange lines intersect). This ratio was found to be 0.9 for the 274-m (900-ft) multicell wall. These results lead to the conclusion that designers should strive to have the area under the wall-to-cross-sectional area ratio around 1.0 for multicell walls. To maintain flow control at the ports, a ratio of 0.9 is recommended. The tow data observed in the physical model experiments indicated the type 4 guard wall produced the most favorable navigation conditions. The angle of the currents approaching the type 4 guard wall from the landside was 16 deg.

The forces computed with the 366- and 274-m (1,200- and 900-ft) floating walls are shown in Figure 29. The ratio $\Sigma A_p/A_x$ of 2.2 balanced the forces with the 366-m (1,200-ft) floating wall and this ratio was found to be 1.8 for the 274-m (900-ft) wall. The results of the experiments performed in the physical model with floating walls indicated the type 10 guard wall produced acceptable navigation conditions. The ratio $\Sigma A_p/A_x$ for this design was 2.0. The angle the currents approached the wall was more favorable for a tow entering the approach with the type 11 guard wall although as mentioned the conditions were considered acceptable with the type 10 guard wall. An area under the wall-to-cross-sectional area ratio of 1.9 is recommended for the floating wall. Tapering the curtains to achieve this ratio will help distribute the flow under the wall better.

A graph of forces as a function of wall flow area for the 366- and 274-m- (1,200- and 900-ft-) long span walls is shown in Figure 30. The ratio of $\Sigma A_p/A_x$ that produces balanced forces with the 366-m (1,200-ft) wall is 0.5 and 0.4 for
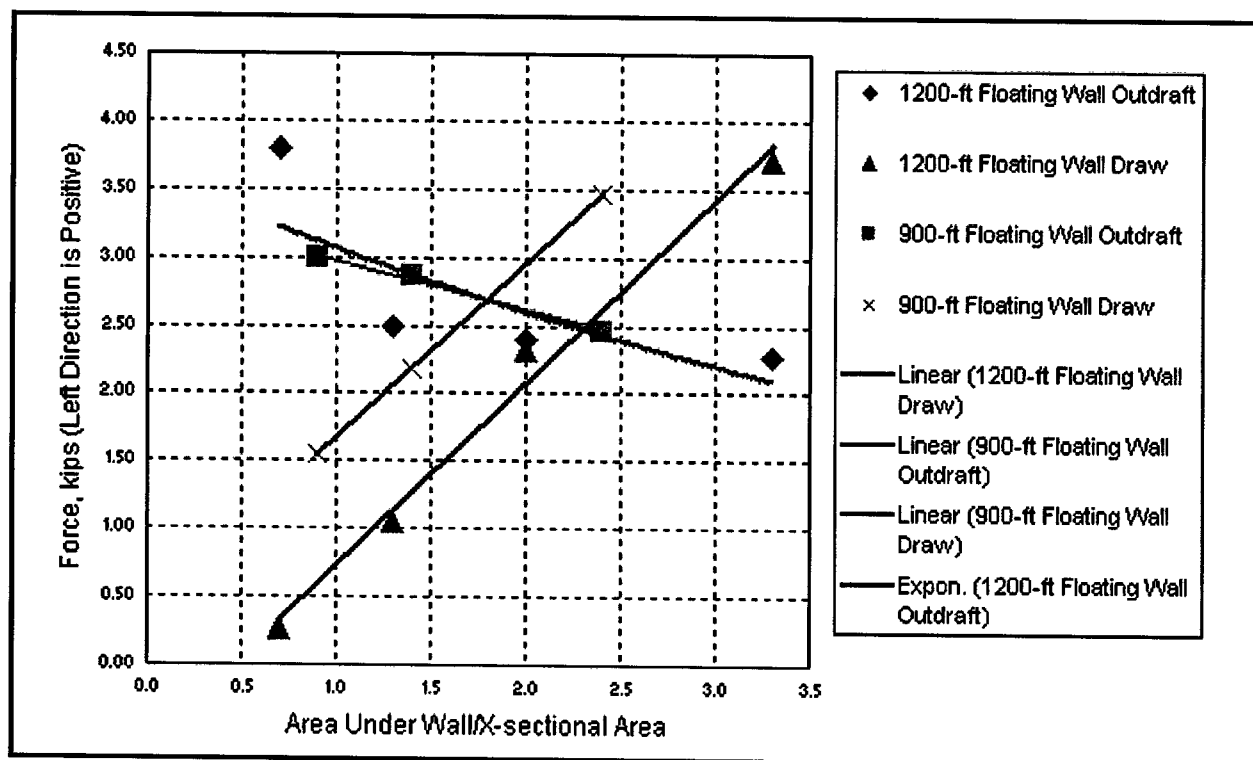
Figure 29. Computed forces with types 9-15 guard walls
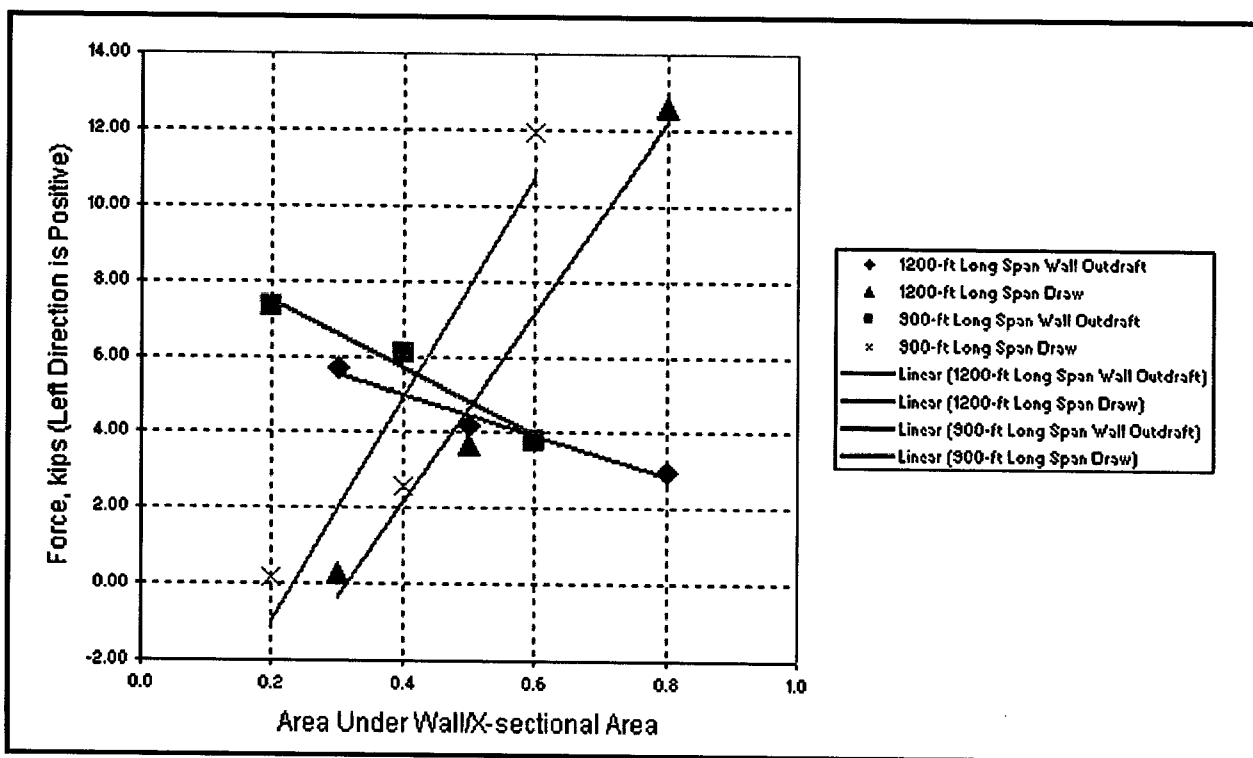

Figure 30. Computed forces with types 16-18 and 22-24 guard walls, 167.6-m (550-ft) approach width

the 274-m (900-ft) wall. These ratios are much smaller than the multicell walls previously described and the floating walls. The approach width was much wider with these designs, which causes the intercepted flow area to be larger if the geometry of the wall remains the same. The forces were not considered excessive with the types 17 and 23 guard walls.

The effect of the larger approach width can be seen by comparing the forces computed for the types 3-5 and 16-18. These designs were the 366-m- (1,200-ft-) multicell walls spaced 15.2 m (50 ft) on centers. A graph of forces as a function of wall flow area for the 168- and 90-m (550- and 300-ft) approach widths with the 366-m- (1,200-ft-) multicell walls is shown in Figure 31. The larger approach width did not improve the navigation conditions. The forces were generally higher with the larger approach width. The navigation conditions were improved with the long span walls and the larger approach width. The increase in total port area with the long span walls helped provide a better $\Sigma A_p/A_x$ ratio to balance forces due to outdraft and draw.
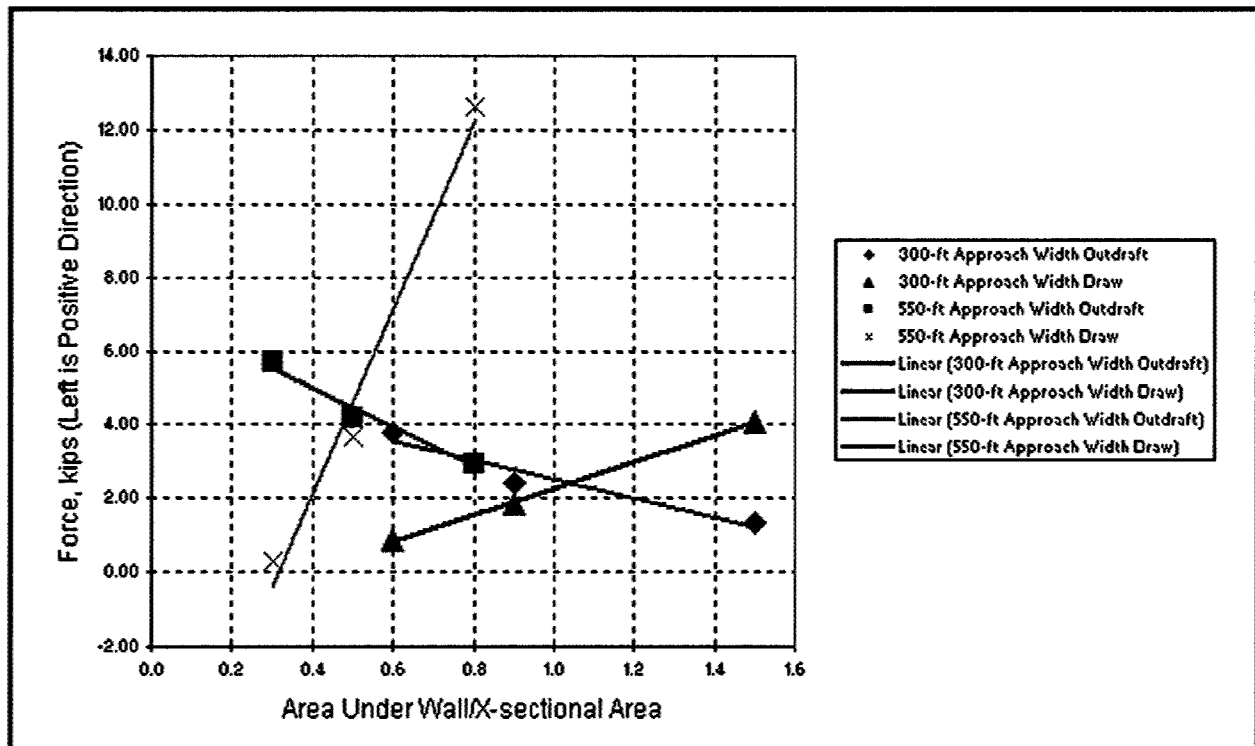

Figure 31. Computed forces with types 3-5 and 16-18 guard walls, multicell walls

These evaluations were intended to indicate the relative acceptability of various guard wall designs. The computed outdraft and draw toward the wall do not capture all of the forces acting on a tow, but rather serve as a means of ranking the designs on the basis of safe navigation conditions. Determination of the optimum navigation conditions is a balancing act between limiting outdraft, by providing more flow area under the wall, and limiting the draw toward the wall resulting from the under-wall flow. The draw toward the wall can cause the tow to strike the wall at an excessive speed and/or inhibit a tow resting on the wall from departing.

Chapter 2   Upper Approach Guard Wall Design

The estimated lateral forces are shown in the bar chart provided in Figure 22. The chart shows that designs such as the solid wall (type 2 design) produce large outdraft but negligible draw toward the wall. Designs that have a large port area such as the type 3 design guard wall (366-m (1,200-ft) multicelled with 0.61-m (2-ft) draft) have little outdraft, but extremely high draw toward the wall. This illustrates that an optimum guard wall design will have to balance outdraft and the draw toward the wall such as produced with the type 4 design.

3 Considerations for Projects Located in Bendways

During the investigation of guard wall design, concern over wall designs for navigation projects located downstream from bends was expressed. An attempt was made to address these concerns based on design information learned and using the numerical techniques adopted for the investigation.

Previous Studies

Sometimes, foundation conditions dictate that a project be located downstream from a bend, for example, lock and dam 14, Arkansas River (Franco and Shows 1971). The development of conditions satisfactory for navigation with the lock on the convex side of a bend is generally difficult. Additional features such as submerged dikes and bank cutbacks must be added to provide safe navigation conditions. When a lock and dam are to be located in a bendway, the regulating works and alignment of the bend should be designed to reduce as much as possible the obstruction to the natural flow of the river produced by the lock and lock walls, reduce the tendency for a point bar to develop, and increase the distance downstream between the point of the convex bar and the end of the guard wall.

Placing the lock along the concave bank so as to provide adequate sight and approach upstream and downstream would produce a serious obstruction to the natural flow of the river, since the lock would have to be located in the deep part of the channel at a considerable distance from the bank. Obstructions produced by the lock and the esplanade will force the high velocity currents moving along the concave bank to change direction rather abruptly and would tend to produce strong crosscurrents near the upper end of the guard wall, which will be hazardous to downbound tows approaching the locks. Ports are required in the upper guard wall of the lock, when placed along the concave bank, to reduce the intensity of the crosscurrents near the end of the guard wall.

The intensity of the crosscurrents near the end of the guard wall can be reduced by increasing the capacity of the guard wall ports (U.S. Army Corps of Engineers 1963). The lock and dam 22, Mississippi River study reported by Wooley (1997b) addresses the many problems associated with a lock located on the inside of bends. A system of dikes was required to provide acceptable navigation conditions for a tow entering and leaving the locks. A ported upper

guard wall, which was long enough to provide protection for the full length of the design tow was recommended. At Aliceville lock and dam, Shows and Franco (1978a) recommended increasing the depth of the approach channel and excavation of a bank in a bend upstream of the project, thus providing a straighter approach.

Bend Experiments

The next phase of this study was to investigate the interaction between the flow exiting a river bend and the flow in the immediate vicinity of the guard wall. That is, can the effects of a bend upstream of a project be quantified in a manner needed for the hydraulic design of a lock guard wall? Experiments were conducted on an existing 1:100-scale physical model of lock and dam 4, Monongahela River. The existing conditions (those of the prototype) at this project were modeled using the numerical modeling techniques previously discussed. The existing conditions are those currently found on the project, which are a 17.1-m (56-ft) wide by 219.5-m (720-ft) long lock and a 17.1-m-(56-ft-) wide by 109.7-m- (360-ft-) long lock and five-bay gated spillway summing to a length of 128.0 m (420 ft). Figure 32 shows the layout and bed contours used in the numerical model. The numerical model was validated by comparing the results to laboratory data. Velocities at 0.6 depth resulting from a discharge of 2,550 m³/s (90,000 cfs) and a pool elevation of 227.66 m (746.9 ft) were measured at points on a 7.62-m (25-ft) spacing across the navigation channel. Navigation channel stations are shown in shown in Figure 33. The
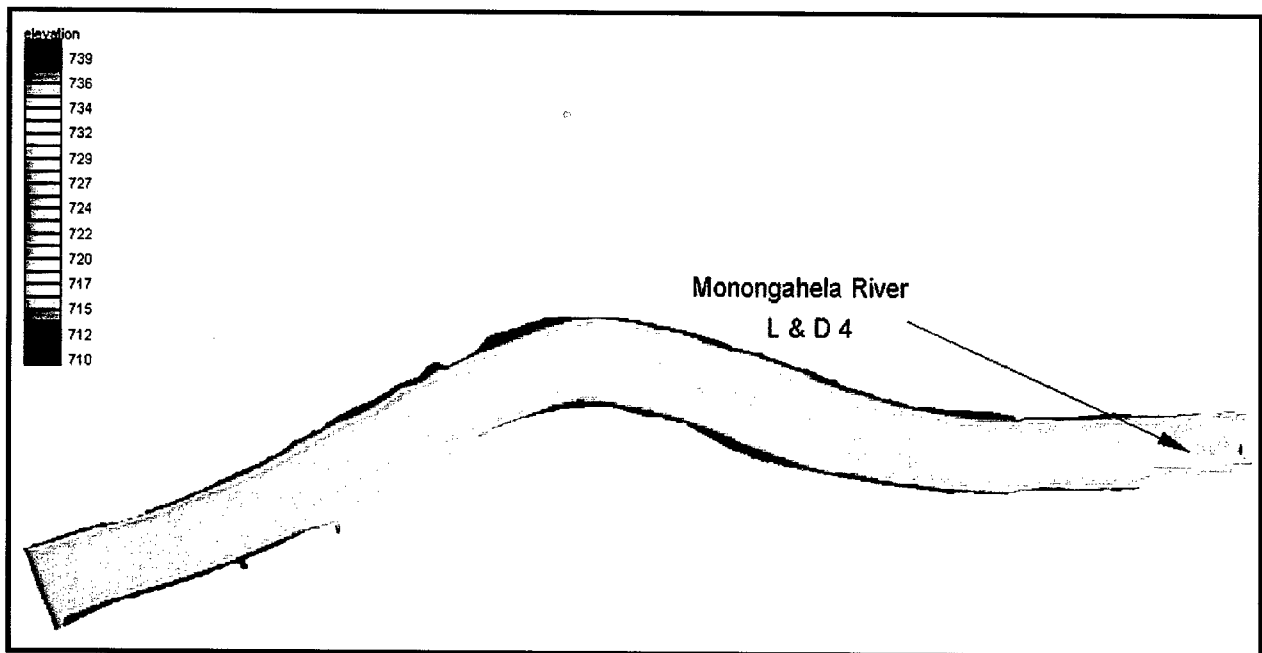

Figure 32. Upper approach to lock and dam No. 4, Monongahela River, bed elevation contours
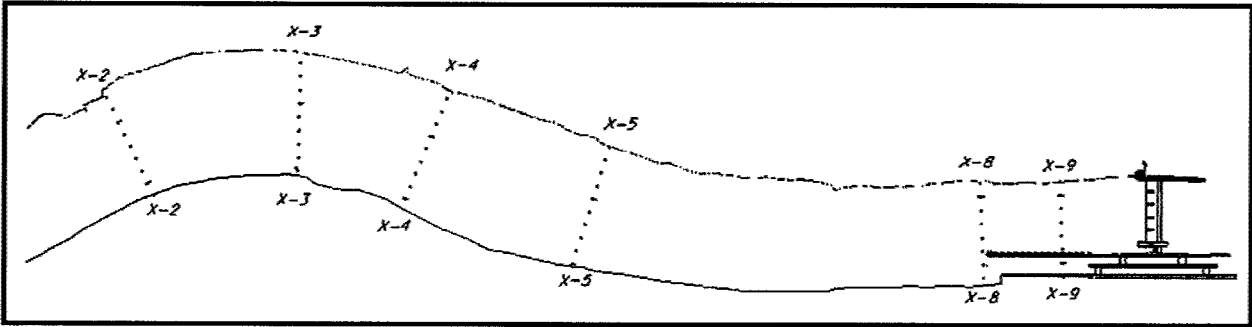
Figure 33. Velocity measurement stations for comparison of numerical model results with physical model data

computed velocities were compared with the measured values at eight stations along the navigation channel. The velocity distributions across the channel for each of the stations are shown in Figures 34-37. The model accurately reproduces the velocities at the cross section upstream of the bend (sta X-2), but does not capture the lateral distribution as well at the cross section just downstream of the bend (sta X-5). However, the velocity profiles illustrate that the computed velocities at the upstream end of the guard wall (sta X- 8) and at a station that crosses the guard wall (sta X-9) compare well with those observed in the physical model.
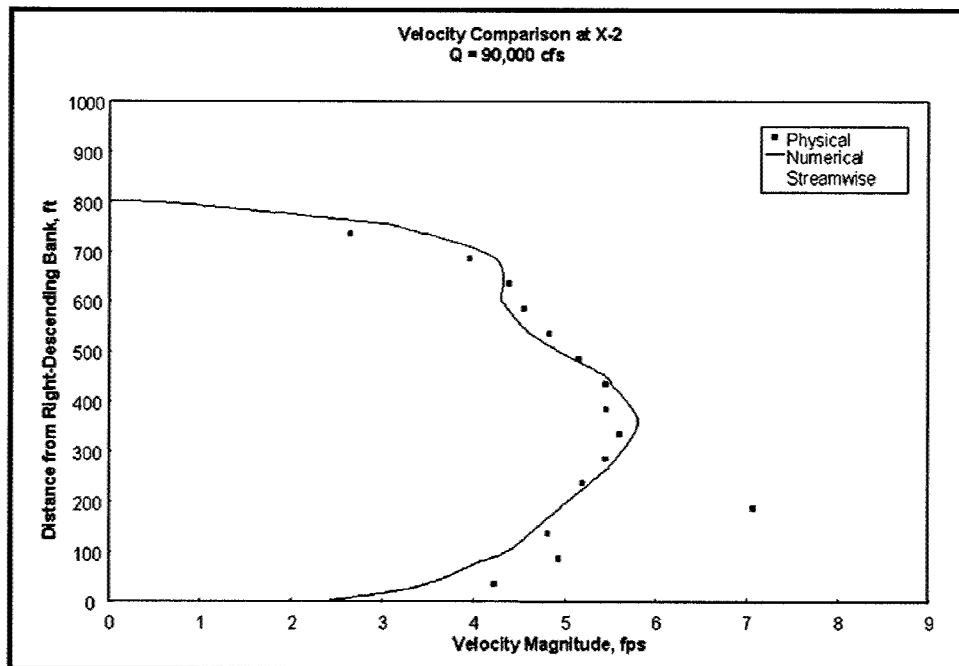

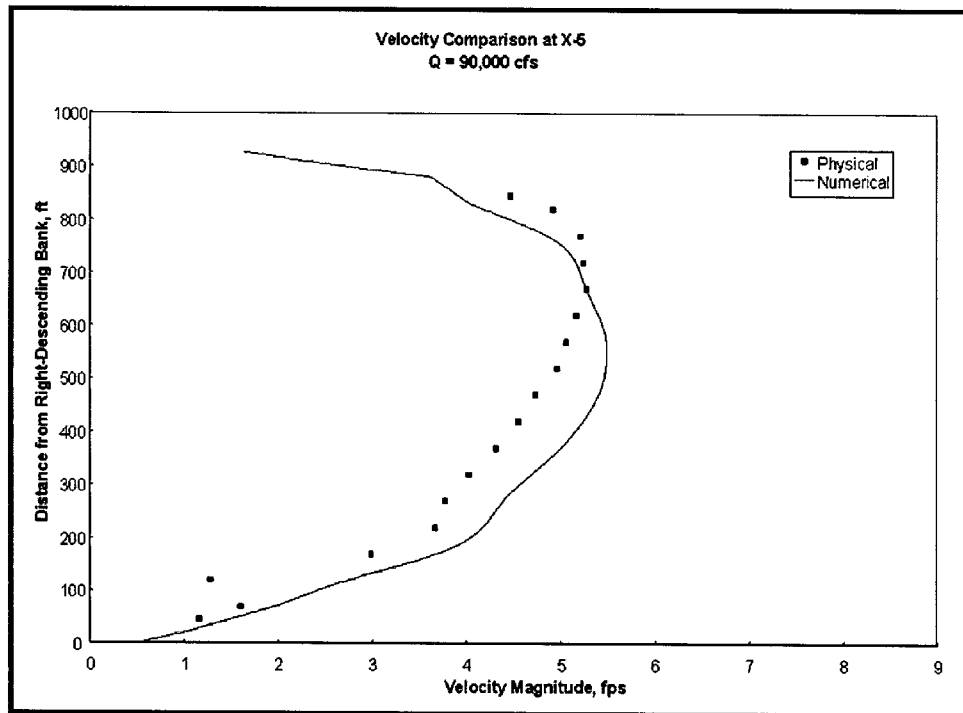Figure 34. Velocity distribution across Monongahela River at sta X-2

Figure 35. Velocity distribution across Monongahela River at sta X-5
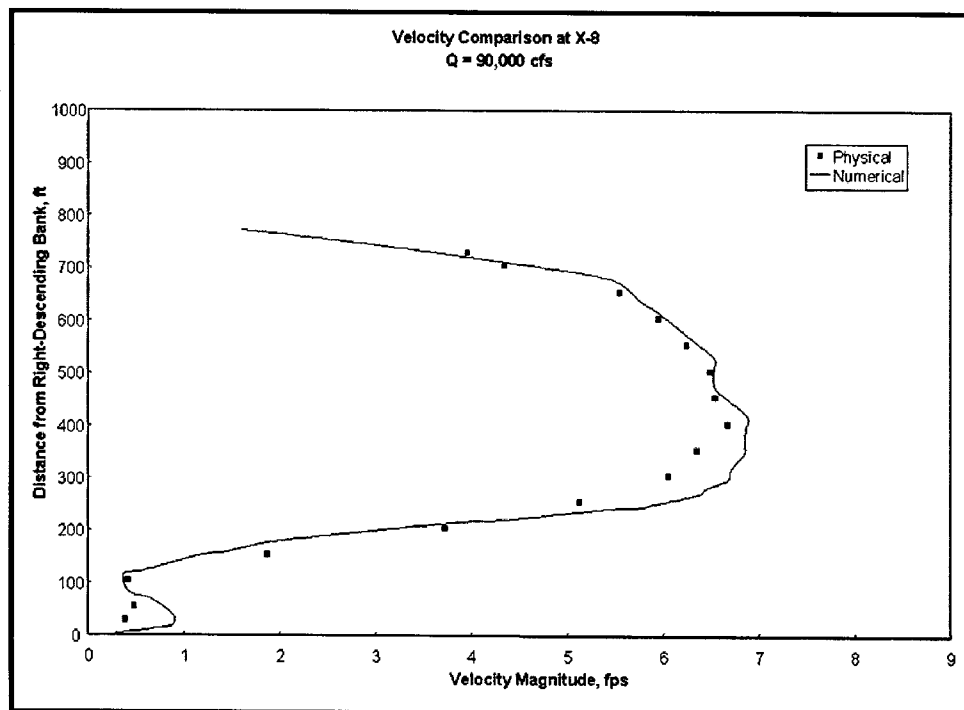

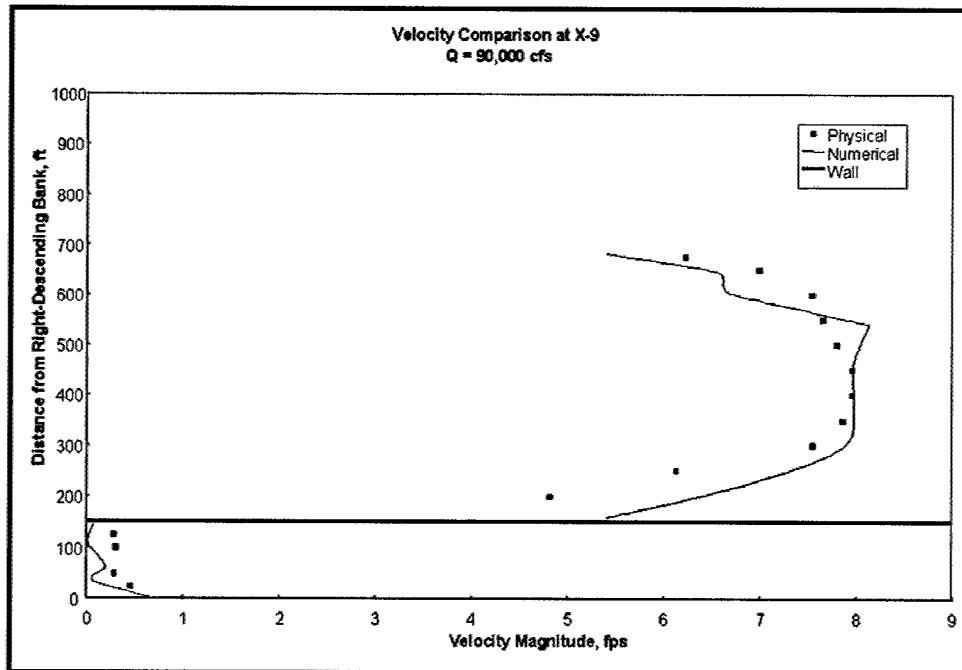Figure 36. Velocity distribution across Monongahela River at sta X-8

Figure 37. Velocity distribution across Monongahela River at sta X-9

The flow associated with several guard wall configurations were computed and subsequently evaluated from a navigation standpoint. This evaluation consisted of computing the lateral forces exerted on a vessel sized for this particular project. The design tow configurations for lock and dam 4, Monongahela River, are 18.5-m (52-ft) wide by 178-m (585-ft) long barge train drafted at 2.74 m (9 ft).

The locks lie on the convex side of the river just downstream of a bend. The guard wall geometry for the designs is listed in Table 2. The results of the multicell and floating wall configurations are summarized in the forces plot shown in Figure 38. The forces were computed from the lateral water-surface gradients from the 2-D model results. As was the procedure with the previous numerical investigation, the flow fields were computed and the resulting water-surface slopes were used to compute forces at various downbound positions as a design-sized vessel approached lock 4. Figure 39 illustrates the forces computed at various vessel positions approaching the lock with type 1B guard wall. The forces indicated that the type 2B guard wall provided the best navigation conditions. This is a multicelled design with a flow area under the wall-to-cross-section intercept area ratios of 1.3. Velocity vectors computed for a multicell wall are shown in Figure 40.

Table 2
Design Information for Guard Walls Evaluated in Bend Experiments

| Design	Wall Type	Wall Length, ft[1]	EL of Bottom (Curtain)	Area Under Wall-to-Cross-Section Area Ratio
Type 1B	Solid	750 ft	NA	0.0
Type 2B	Multicell	750 ft	744	1.3
Type 3B	Multicell	750 ft	736	0.9
Type 4B	Multicell	750 ft	731	0.6
Type 5B	Floating	750 ft	723	0.4
Type 6B	Floating	750 ft	725	0.6
Type 7B	Floating	750 ft	727	0.9
[1] Units in this table are in feet. To convert to meters, multiply by 0.3048.				
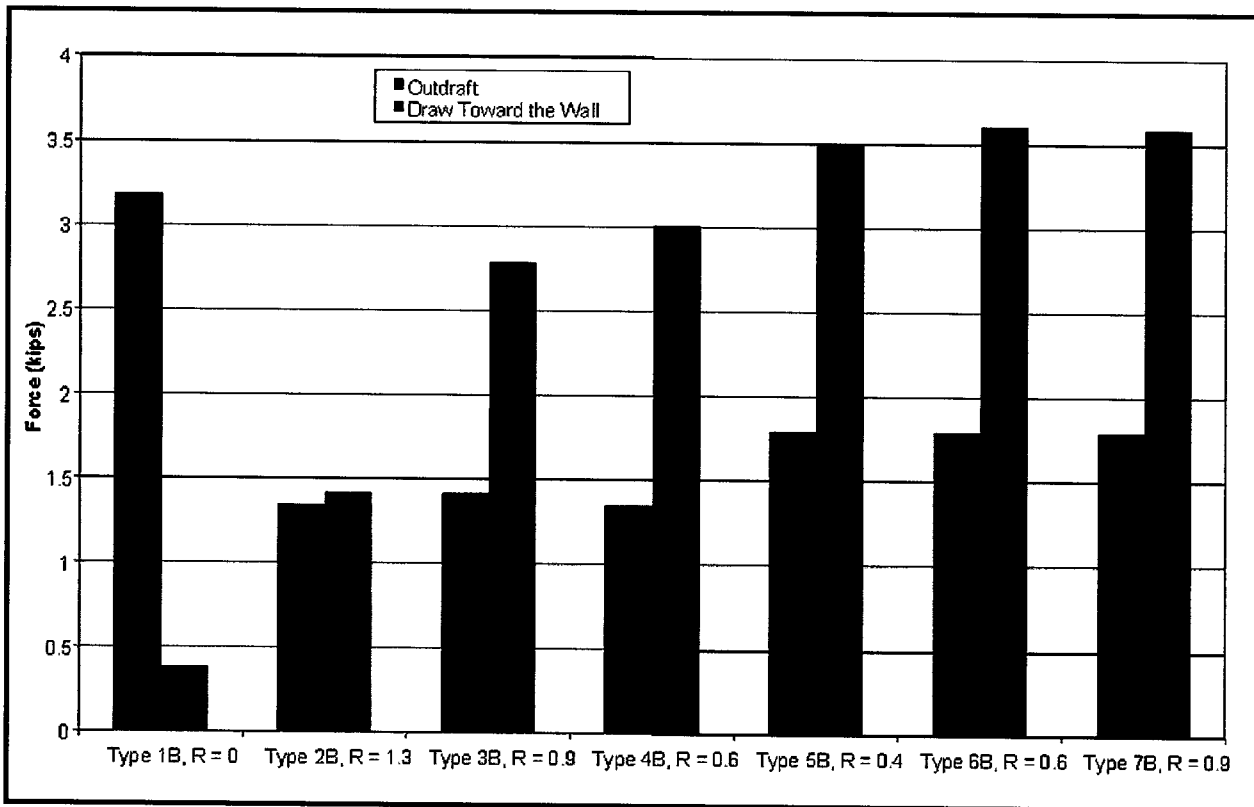
Figure 38. Computed forces due to outdraft and draw for bend experiments,
R = flow area under the wall-to-cross-section intercept area ratio
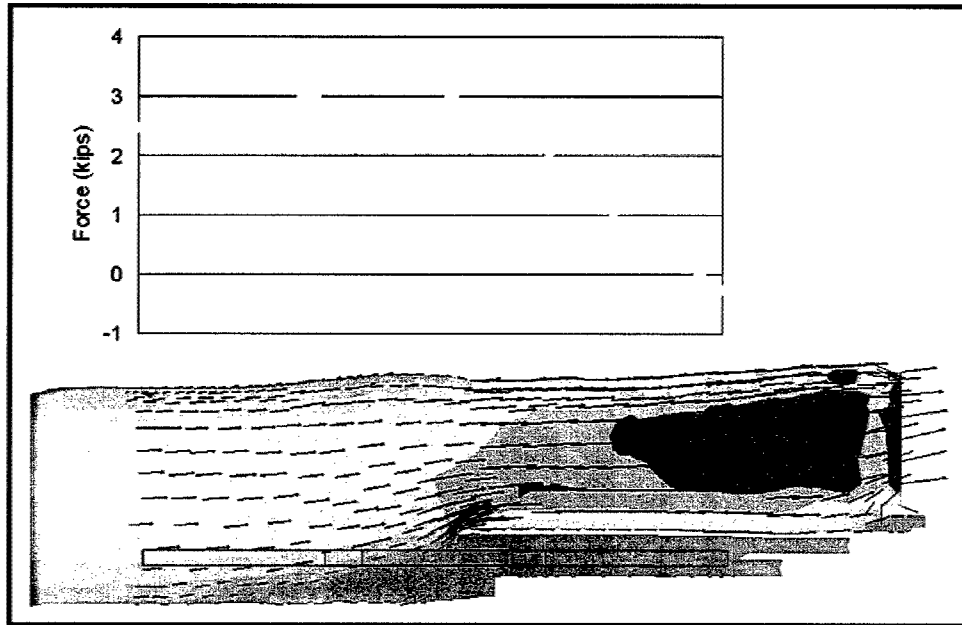
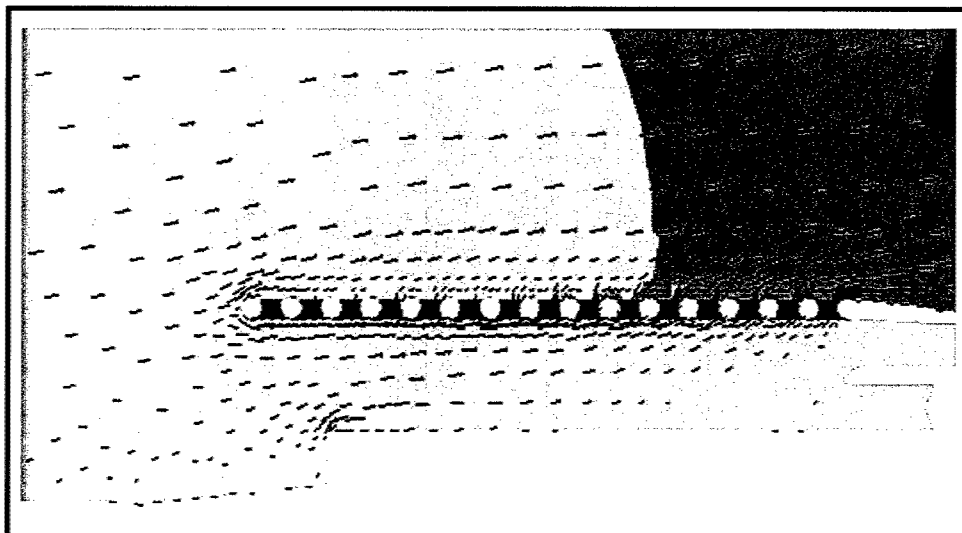Figure 39. Example of forces computed on tow during lock approach with solid wall

Figure 40. Velocity vectors with multicell guard wall in bend experiments

Design Recommendations

Numerical model experiments with various wall configurations for the lock placed downstream of a river bend lead to the following generalized conclusions. The solid guard wall produces flow conditions in which the outdraft is largest. The multicell wall having an area under the wall-to-cross-section intercept area ratios of 1.3 provided the best balance of draw toward the wall and outdraft. Although outdraft with the multicelled wall varied little for the configurations examined, the draw was found to increase as the area under the wall was increased. For the range of geometries tested with the floating wall (area under the wall-to-cross-section intercept area ratios of 0.4 to 0.9), the outdraft and draw varied little. Each floating wall had more draw than the multicelled wall. These results are not a result of the project being located downstream of a bend as much as they are from the fact that the existing project is functioning quite well as is. Most of the differences in flow conditions associated with the various wall configurations are attributed to the circulation patterns between the guard wall and near shore. The shape and size of the eddy in front of the locks, between the guard wall and the bank, varied by guard wall design. This circulation provided water-surface slopes near the right bank toward the bank rather than toward the lock wall. The results of the modeling of a project downstream of a bend should be taken as a demonstration of a modeling capability rather than the development of design criteria. The site-specific conditions often prevail in lock approach design and lend themselves to a computational model for initial design configurations rather than generalized design guidance.

4 Summary and Conclusions

This study has provided two products, which are helpful to engineers tasked with designing guard walls. The first is a method of using an existing 2-D depth-averaged numerical model to simulate the flow under and around the guard walls. This method employs a specified pressure field to simulate the draft of the wall. The wall blockage is modeled with the mesh boundaries representing the piers and the pressure field imposed on the water surface to represent the wall draft into the pool.

Secondly, the results of numerous physical and numerical model experiments have been combined to determine hydraulic considerations for the basic layout of guard walls. The approach width, wall length, and skirt depth all affect navigation conditions in the upper lock approach.

The following table lists the optimum design ratios produced by the experimental data. These ratios reflect those geometries, which produce optimum navigation conditions for the flow and channel conditions tested.

Approach Width = 91.4 m (300 ft)		
Wall Type	Length	$\Sigma A_{ports} / \Sigma A_{xs}$
Multicell guard wall	366 m (1,200 ft)	0.9
Long-span guard wall	366 m (1,200 ft)	1.4
Floating guard wall	366 m (1,200 ft)	1.9

It should be noted that the ratios listed are specific to the wall type and are a recommended starting point for guard wall configuration.

No generalized design guidance was provided by the experimental program involving projects located downstream of river bends. As with the generalized research, numerical model experiments showed that solid guard walls produce more outdraft and essentially no draw as compared to ported walls. The multicelled wall having an area under the wall-to-cross section intercept area ratios of 1.3 was found to be the best guard wall design. No significant differences were found for each of the floating walls modeled. No generalized design guidance can be drawn from the limited experiments conducted with projects located downstream of bends, but the guidance for straight approaches should provide a good starting point for hydraulic design of a lock approach. Projects associated with complicated river bathymetry can be modeled using a 2-D model with the methods described in this report. These model results should

provide a good indication as to what guard wall configurations might be suited at a particular site.

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14. ABSTRACT

Upper lock approach guard walls are structural features used by towboats to align with and enter the lock chamber. This report focuses on guard walls located in the upper lock approach. The performance of these guard walls drastically impacts the functional efficiency of any given lock. An efficient guard wall minimizes pilot maneuvering required to bring a tow to rest or near rest on the guard wall and align with and enter the lock chamber. In addition, guard walls are a major component in overall project cost.

Criteria for evaluating guard wall performance are general and limited. This report provides guidance so that engineers can design lock approach guard walls that are safe and efficient to the users, while being cost-effective. Both physical and numerical models were used to help research guard wall design and develop guidance for design. A literature review was used to assist in identifying pertinent design needs and to develop the testing and evaluation program. A physical model was constructed so that a detailed evaluation could be performed for selected guard wall designs. A numerical model was used to help rapidly evaluate numerous designs and identify the designs to refine in the physical model.

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